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Digital Edition
FUTURE
VOLUME 11
Everything you want to know about our galaxy and beyond

ALL ABOUT SPACE Annual

Following a busy 2022, the year 2023 has brought even more excitement to the world of space exploration. NASA's Artemis program, which aims to send astronauts back to the Moon by 2025, made a successful launch with Artemis I at the end of last year. At present, the program is preparing for its second mission, Artemis II, where four astronauts will orbit the Moon and return to Earth in 2024. Meanwhile, the James Webb Space Telescope is making groundbreaking discoveries, providing us with incredible new insights into the universe. To learn more about these missions and more, check out this year's All About Space Annual. Inside, you'll also discover the secrets of the Solar System, the mysteries of deep space, and even delve into the world of space science.

ALL ABOUT SPACE Annual

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SOLAR SYSTEM

Discover the secrets of our fascinating planetary system

“We can thank Jupiter for protecting our planet from devastating collisions”
Andrew May

MYSTERIES OF THE UNIVERSE

SOLVING THE SUN'S BURNING MYSTERY

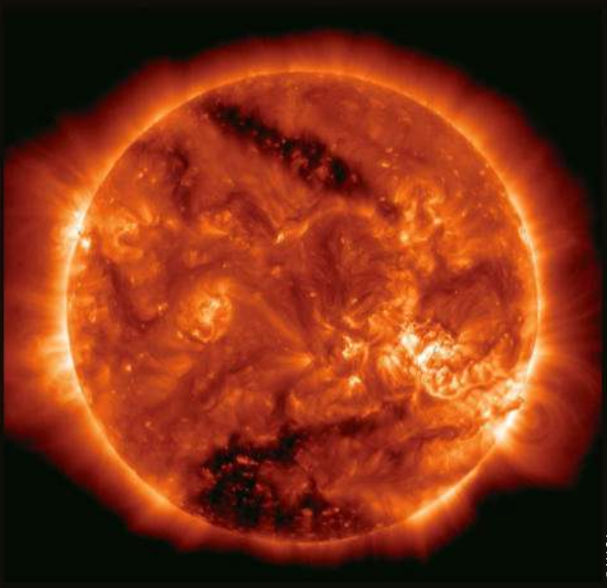
Scientists have spent decades trying to figure out why the Sun's atmosphere heats to extreme temperatures

Reported by David Crookes

Walk carefully over to a fire and you'll find it gets hotter the closer you get. As you walk away you start to feel cooler again. But if you were to do that at the surface of the Sun, the opposite would happen. You'd walk away from the intense heat, start to feel cooler and then suddenly begin to feel hot again. Moving far away from this hot source only puts you in the midst of an even hotter upper atmosphere. Although the Sun's surface burns at a blisteringly hot 6,000 degrees Celsius (10,800 degrees Fahrenheit), the outermost layer of our host star's atmosphere – which extends thousands of miles above the visible surface – reaches temperatures of around 1 to 2 million degrees Celsius (1.8 to 3.6 million degrees Fahrenheit). It's a mystery that's perplexed scientists around the world for decades. Just what is heating the atmosphere to such extreme temperatures? Numerous theories have emerged, each seeking to shed light on the corona's physical properties and how they've come to be. But while the debate rages on, with a number of different promising ideas, astronomers may now be closer to an answer than ever before.

This solar puzzle has a name – the coronal heating problem – and was born in the 1940s. Astronomers had long been investigating the temperature of the Sun by this point, but this was the decade in which the million-degree temperature of the atmosphere was discovered spectroscopically. "As with many other things in space, we know how hot the Sun is by looking at the light that comes off it," explains Dr Jonathan Squire of the University of Otago in New Zealand. "It's just like the intuitive notion we have that 'red-hot' is pretty hot, but 'white-hot' is much hotter. From this we know that the light we see from the Sun is around 6,000 degrees Celsius [10,800 degrees Fahrenheit], and in the corona the same sort of idea applies. Here we look at the light released by specific elements, which emit light at discrete colours. In the corona, it was realised in the 1940s that some of these colours, known as spectral lines, come from iron that has lost many of its electrons, which implies that it must be extremely hot. But why?"

Squire has been working on the problem with Otago's Dr Romain Meyrand and scientists at Princeton University and the University of Oxford. The idea was to get to the bottom of how magnetic fields, which thread out of the Sun's surface, work to heat the gas. "We know from measurements and theories that the sudden temperature jump is related to magnetic fields," Squire asserts. This has been known since the 1960s. "That's when scientists were able to take pictures of the corona in X-rays – it's so hot that it's like a light bulb shining with X-rays rather than visible light, or even ultraviolet," Squire tells **All About Space**. "This showed



Here you can see two coronal holes in the Sun, captured by NASA's Solar Dynamics Observatory in 2015

THE SUN'S CORONA BY NUMBERS

10 MILLION
times less dense than the surface of the Sun

10 BILLION
times less dense than Earth's atmosphere at sea level

300
times hotter than the lowest layer of the Sun's atmosphere

1 MILLION
Minimum temperature of the corona in Celsius

400
KILOMETRES PER HOUR
Speed at which corona particles are transported through space by solar wind

7,200,000
KILOMETRES PER HOUR
Fastest recorded coronal mass ejection

that the strongest emission, so the hottest gas, was strongly concentrated and shaped by the magnetic field. You can see similar features on pictures of the corona taken during solar eclipses." Since then, he adds, the magnetic field has been measured directly through spectral lines and colours of light, again showing the corona's temperature is directly correlated to the magnetic field complexity. "We can also measure the energy content released upwards in magnetic fields and see that it's more than enough to satisfy the heating requirements."

To get to the bottom of this pressing problem, the team examined two well-studied theories – one involving energy transfer and the other a type of magnetic wave – and wondered if they could be linked. On their own, each theory has issues in fully explaining how the corona is able to become so hot. But there was a chance, the team surmised, that one could explain the shortfalls of the other. The method they used was to simulate the coronal gas on a supercomputer, based on a hunch that the two theories would be linked by a new effect called the 'helicity barrier' that was proposed in an earlier study led by Meyrand. It was designed to study a small 'patch' of the corona or solar wind. "Just a tiny box moving outwards with the wind," Squire says. And the main job, he adds, was just to set it up and understand what was happening. "This was a non-trivial task," he adds, "because the simulation made about 30 terabytes of data."

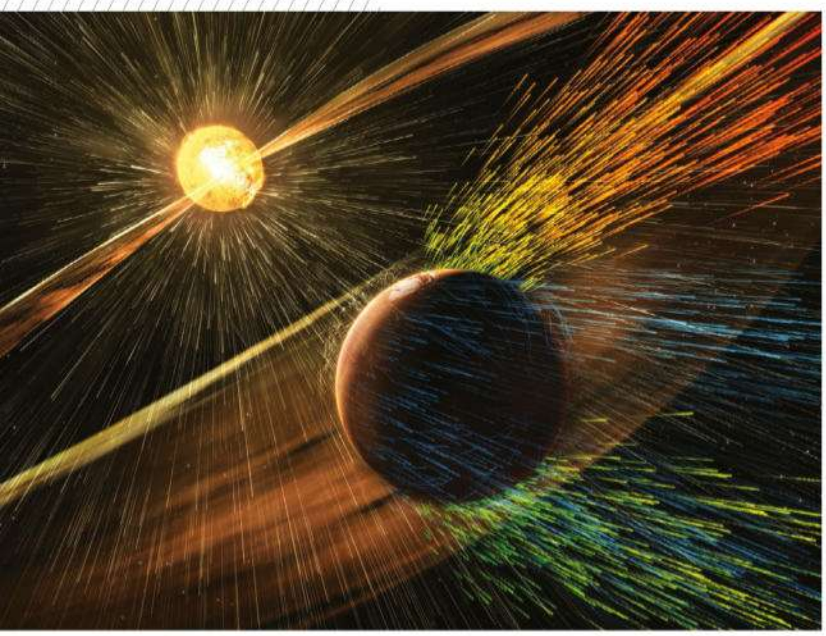
The first theory under scrutiny involved low-frequency Alfvénic turbulence heating the corona through a transfer of energy outwards from close to the Sun. But it has run into problems because what happens in theory is not what is seen in observations. "It's fair to say that there are some issues with theories of heating of turbulence," says Squire. But what are the issues? "Unlike

gas here on Earth, different species in the corona can have different temperatures, and this is a bit weird," he explains. "The reason is that particles collide very rarely with each other – hydrogen particles only collide about once in the time it takes them to travel all the way from the Sun to Earth, for instance, so there's nothing to make them have the same temperature."

During turbulence – random, chaotic eddies of gas or plasma – the different particles are stirred up in different ways, causing their temperatures to change. "How this actually happens depends on the conditions that the plasma is in," Squire continues. "When the magnetic field is dominant, like in the corona, the simplest theories of turbulence – backed up by simulations – suggest that electrons should be heated more than hydrogen. But this is the opposite of what we observe." In other words, observations made by telescopes and spacecraft show that the electron-stripped cores of the hydrogen, helium and oxygen atoms, or ions, are becoming superheated while the electrons remain relatively cool in the corona. There have been proposals that seek to get around this difference between theory and reality, but the physics remains poorly understood.

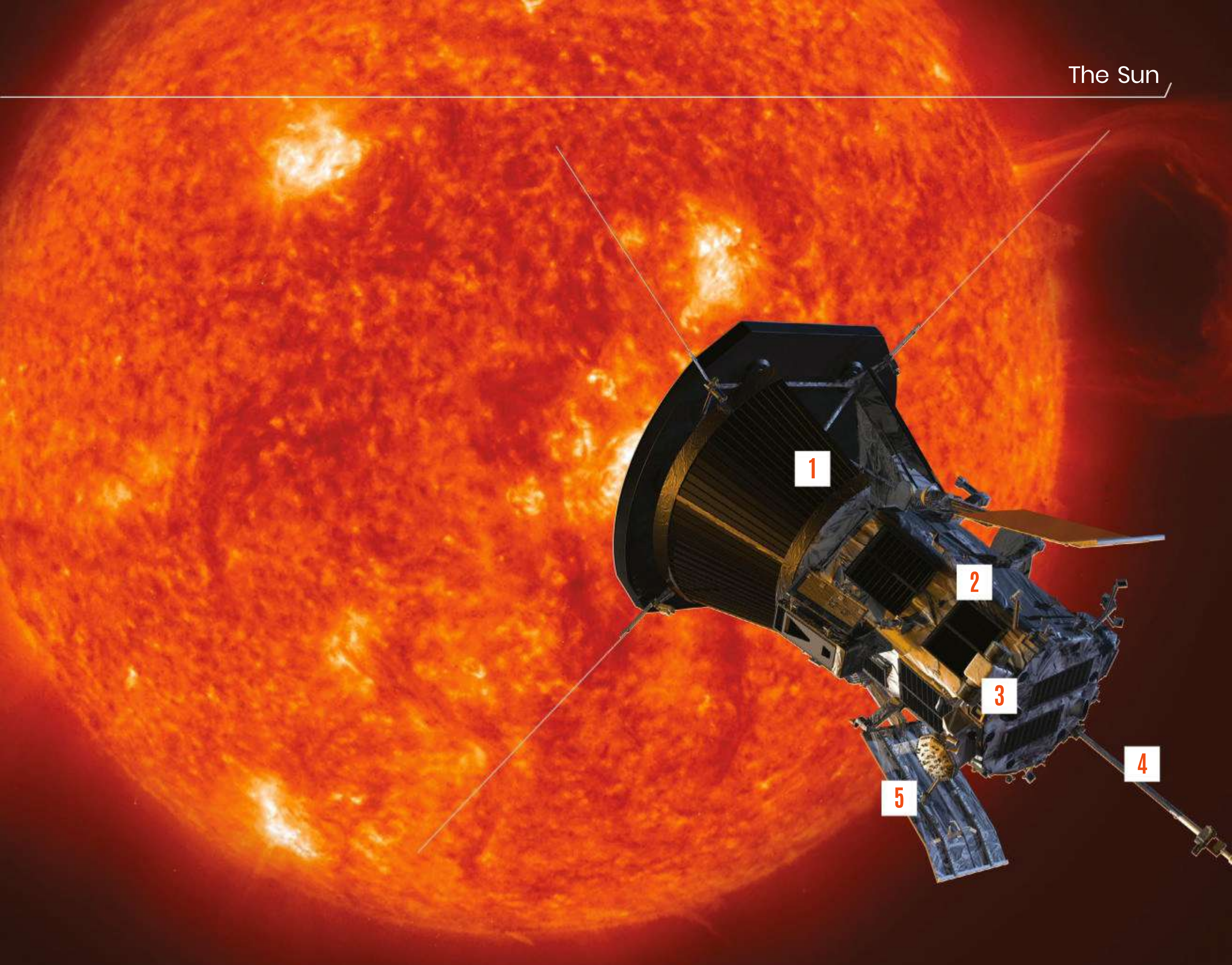
Similarly, a theory that the corona is being heated by a type of magnetic wave called ion cyclotron waves runs into problems for a very simple reason. "For ion cyclotron waves to cause heating, there must be a source of them," Squire says. "There has been good evidence from radio measurements that there are not very many of them coming directly off the surface of the Sun, so that's our fundamental problem – where do they come from?" The simulation borrowed from both theories, showing they are linked by the helicity barrier effect – but what is this?

"One way that physicists think about turbulence is that it's a 'flow' of energy from



The corona, which lies above the chromosphere, can be seen as a halo during a solar eclipse

Understanding the Sun's atmosphere gives scientists a better grip on the solar wind, which can cause damage here on Earth and even on planets further afield



STUDYING THE SUN

NASA's Parker Solar Probe has flown through the corona – the first spacecraft to get so close

1 Taking samples

The Parker Solar Probe was launched in 2018. It flew through the corona to sample particles and magnetic fields in December 2021. There are spikes and valleys that wrinkle the surface.

2 Protection

To enable the probe to withstand the extreme heat of nearly 1,377 degrees Celsius (2,500 degrees Fahrenheit), as well as radiation, it has a thick carbon-composite shield. The payload is at near room temperature.

3 Primary goals

The probe is tracing how energy and heat move through the corona. It's also exploring what accelerates the solar wind and solar energetic particles.

4 Comparative study

Squire and his team say the structures and eddies forming in their simulation are similar to the measurements being taken by the probe.

5 Instruments

The probe's Electromagnetic Fields Investigation instrument captures the shape and scale of electric and magnetic fields. Solar Wind Electrons Alphas and Protons counts solar wind particles and measures its properties.

SLICING UP OUR STAR

1 SOLAR CORE

Temperature:
Over 15 million degrees Celsius (27 million degrees Fahrenheit)
Density:
150 grams per cubic centimetre

2 RADIATIVE ZONE

Temperature:
1.9 million degrees Celsius (3.5 million degrees Fahrenheit)
Density:
From 20 to 0.2 grams per cubic centimetre

3 CONVECTIVE ZONE

Temperature:
1.6 million to 5,540 degrees Celsius (3 million to 10,000 degrees Fahrenheit)
Density:
$2x10^{-7}$ grams per cubic centimetre

4 PHOTOSPHERE

Temperature:
5,540 degrees Celsius (10,000 degrees Fahrenheit)
Density:
10^{-9} grams per cubic centimetre

5 CHROMOSPHERE

Temperature:
5,540 to 20,000 degrees Celsius (10,000 to 36,000 degrees Fahrenheit)
Density:
10^{-12} grams per cubic centimetre

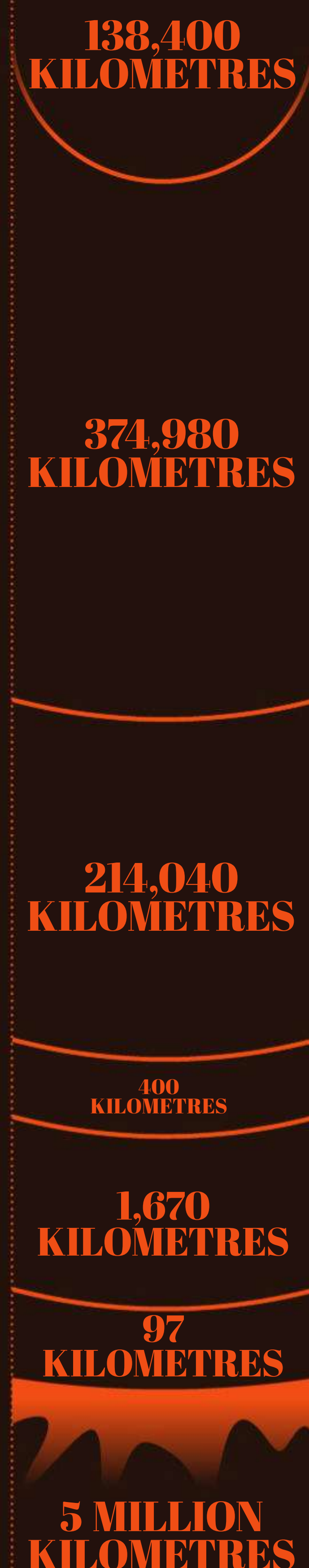
6 TRANSITION ZONE

Temperature:
22,200 to 1 million degrees Celsius (40,000 to 1.8 million degrees Fahrenheit)
Density:
$2x10^{-13}$ grams per cubic centimetre

7 CORONA

Temperature:
1.1 to 1.6 million degrees Celsius (2 to 3 million degrees Fahrenheit)
Density:
10^{-16} grams per cubic centimetre

THICKNESS OF SOLAR LAYERS



large scales [big eddies] to small eddies where energy becomes heat," Squire says. To explain this, he draws comparisons with cream in your coffee. "It starts out large scale and unmixed because your spoon is large and makes large eddies, but the motions of stirring break up and twist the cream to smaller scales, and eventually it becomes small enough that the cream mixes into the coffee."

He says that this last step is like the conversion of the magnetic and kinetic energy into heat in the corona. What the study proposes, however, is that something gets in the way of the flow. "The helicity barrier is a very weird feature of strongly magnetised plasmas that stops the process of eddies breaking up. They get smaller and smaller and then suddenly can't any more because of the helicity barrier," Squire continues. "If we imagine the flow of energy to smaller scales to be like a river flowing down a hill, then the helicity barrier is like placing a dam halfway. The energy flow is stopped by the dam, meaning the energy grows because it keeps arriving from larger scales. Eventually, it 'spills over'. This makes some of the magnetic waves that absorb the spillover [the energy], and this last step is what we showed in the simulation. The helicity barrier links the two theories."

The simulation involved emulating the process of the larger eddies stirring up the smaller ones by adding an artificial spoon to stir up the plasma in the box. The scientists watched the turbulence develop and measured its properties as it did so. What's more, the study's findings seem to tally with other data – notably that being gathered by NASA's Parker Solar Probe, which is the first spacecraft to have flown into the solar corona. "The nice thing – and one of the main features of the study – is that when all of this complicated stuff happens with the helicity barrier and the ion cyclotron waves, we serendipitously explain lots of other features that are seen by spacecraft in the solar wind, such as the Parker Solar Probe. "You can see the helicity barrier operating by effectively measuring the shape of the eddies, and we see the same features in the solar wind."

Although Squire and his team stop short of claiming the mystery is solved, they are aware they have made a big step towards better understanding the cause of the heating. And while their work relates to the continuous heating of the corona as opposed to the extreme, bomb-like coronal mass ejections, knowing more about what makes the Sun's atmosphere tick and understanding the solar wind can help us better predict future space weather and avoid devastating problems. "Coronal mass ejections – where part of the corona gets incredibly hot and then explodes out into space – can cause havoc if they hit Earth," Squire says. Indeed, when the solar wind interacts with Earth's magnetic field, it can disrupt satellites providing services such as GPS, affect the power grid, hit radio communications and impact astronauts on the International Space Station. The cost could run into the billions.

"We think we have good evidence of the helicity barrier operating and the process actively occurring, at least in the altitudes of around 20 solar radii, which is now being explored by the Parker Solar Probe," Squire says. "Knowing this, we infer that the heating process – the waves – is also related. This is all a continuous process of comparing our data to observations. If we had the best theory in the world for how it all happened but it disagreed with the observations, then it wouldn't be much good."

SOME HOT TAKES

Scientists have come up with a host of hypotheses

Magnetic waves

In 1942, Hannes Alfvén said large amounts of energy could be carried by magnetised waves of plasma from the Sun's surface to the corona along magnetic fields before bursting with heat. The existence of these waves was confirmed in 2021.

Bursts of heat

Tiny eruptions called nanoflares occur in the corona; they are one-billionth the size of normal solar flares. One theory by Eugene Parker says these could be keeping the corona hotter than the surface of the Sun.

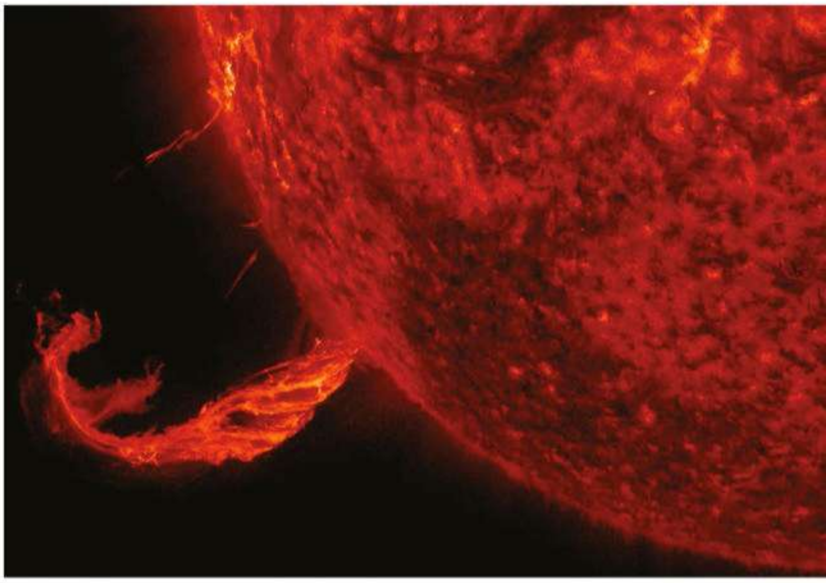
Energy transfer

The outer layer of the Sun is in a state of constant turbulence, and it's known that energy is being transferred outwards from the Sun. But observations show that ions are heated more than electrons, and this theory suggests the opposite would happen.

The helicity barrier

The latest study suggests that low-frequency turbulence is halted by an effect called the helicity barrier which limits electron heating and diverts the energy into ion cyclotron waves, which then causes high-frequency heating.

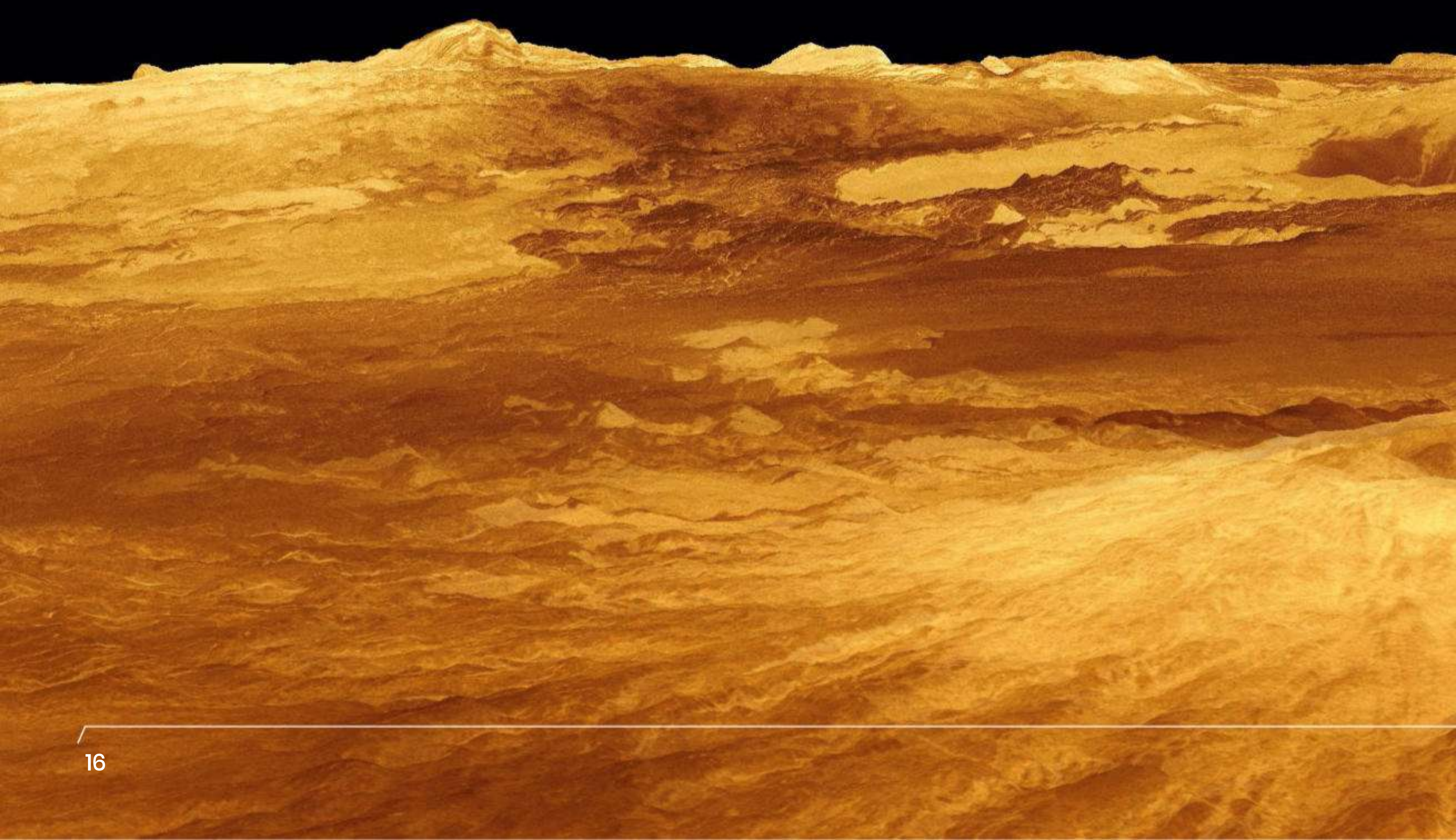
David Crookes
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.


Huge clouds of solar plasma and magnetic fields are sent into space – a coronal mass ejection in action

22 THINGS YOU DIDN'T KNOW ABOUT VENUS

Earth's sister planet is an intriguing and mysterious world, with much more to it than meets the eye

Written by Lee Cavendish



1 VENUS HAS A RICH HISTORY

Studies of Venus can be traced back to the ancient Babylonians in 1600 BCE. They tracked the movement of several planets and stars. The oldest astronomical document on record is a Babylonian diary of Venus appearances over a 21-year period. Venus played a serious part in the mythology of ancient civilisations, including the Maya and Greeks. Its name comes from the Roman goddess of love and beauty.

2 THE PRESSURE'S ON

Walking around on Venus would be an unbearable experience for astronauts for several reasons, but one of them is the extreme pressures on the surface. The atmosphere creates air pressure that's over 90 times the air pressure on Earth, which is similar to the pressure around a kilometre (0.6 miles) deep in the ocean.

1 Atmosphere

96.5 per cent is carbon dioxide, with nitrogen, sulphur dioxide, argon, carbon monoxide, helium and more.

2 Crust

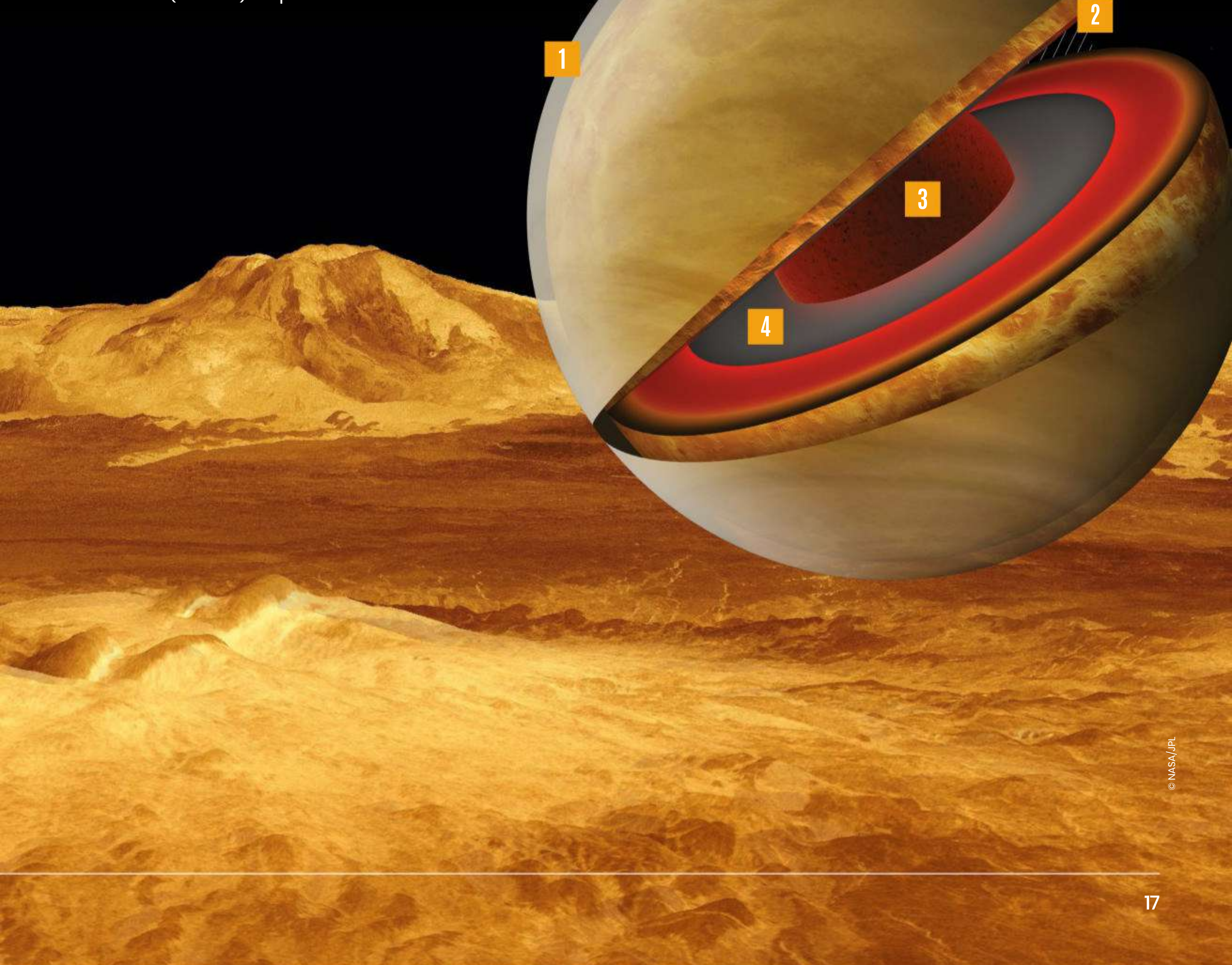
Venus' crust is made of silicate rocks and is estimated to be 50 kilometres (31 miles) thick.

3 Metallic core

Venus' iron core consists of a solid inner and liquid outer core 3,200 kilometres (2,000 miles) in radius.

4 Molten mantle

The heat from the core creates a molten mantle that is 3,000 kilometres (1,200 miles) thick.



3 IT'S SIMILAR TO EARTH

When looking purely at the physical parameters of Venus, it's remarkably similar to Earth. They're almost the same in size and density, their compositions are similar and they both appear to have relatively young surfaces that are surrounded by an atmosphere with clouds. It's worth stating that Venus' clouds are primarily sulphuric acid though, which isn't something that you'd want raining down on you.

4 IT'S JUST A PHASE

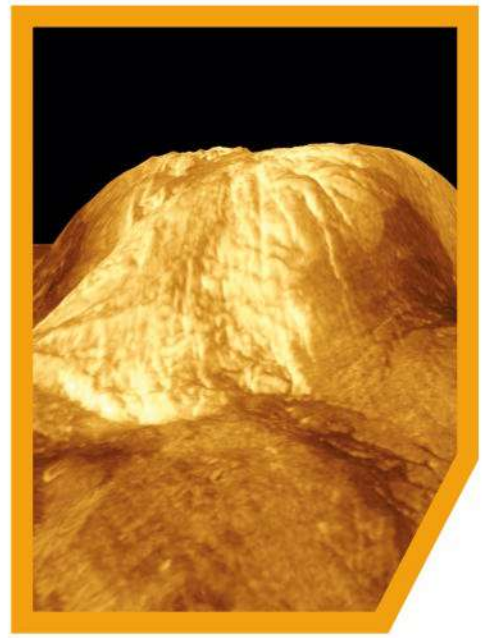
Venus experiences different phases, just like the Moon. As Venus travels around the Sun within the orbit of Earth, it changes between a 'morning star' and 'evening star' roughly every nine-and-a-half months. During this period it shifts between different percentages of illumination, a trait that is normally associated with the Moon.

5 TRANSITS ARE VERY RARE

Venus is one of two planets that orbit the Sun within the orbital path of Earth. Along with Mercury, these two planets can find themselves between Earth and the Sun, sometimes creating a silhouette that moves across the Sun over a period of hours. These journeys are known as 'transits', and Venus is known to transit in pairs – though with over a century separating the pairs, it's a very rare event.

6 IT'S HELLISHLY HOT

Venus is the hottest planet in the Solar System, even hotter than the dayside of Mercury, which has temperatures of 427 degrees Celsius (801 degrees Fahrenheit). Because of Venus' thick, carbon dioxide-rich atmosphere, the heat is efficiently retained, creating surface temperatures higher than 470 degrees Celsius (880 degrees Fahrenheit).



7 VENUSIAN VOLCANICITY

To add to the hellish image of Venus, it also has the most volcanoes present on the surface of all the planets in the Solar System. On Earth there are 1,500 known active volcanoes, and Mars is best known for the largest volcano in the Solar System, Olympus Mons. However, Venus has over 1,600 major volcanoes, and that's not including the smaller ones or any that haven't been detected yet.

8 IT DOESN'T HAVE A MOON

Venus and Mercury are the only planets in our Solar System that don't have their own moon. It's a bit more understandable why Mercury doesn't have a moon, because its close proximity to the Sun has a negative effect on any contenders. The planet is also smaller than some Solar System moons, such as Jupiter's Ganymede and Saturn's Titan. However, researchers have argued that the reason Venus doesn't have a moon isn't as simplistic. There are two theories: the first is that any moon that Venus had was stolen by the Sun's gravity. The second is known as the 'double-impact theory', which states that a large celestial body hit Venus billions of years ago, creating a moon in a similar way to how Earth got its lunar companion. But several million years later, an even bigger object hit Venus, causing its retrograde rotation, weakening the tidal forces and sending the moon to sink into Venus, never to be seen again.

9 EARTH VS VENUS

The Sun

On Venus, the Sun would appear no more than a dimly glowing patch through the thick clouds.

Clouds

Venus is enveloped in clouds, not allowing any nosey astronomers to investigate the surface. While Earth is also hidden by clouds, much more of our planet's surface is visible from space.

Surface rocks

Based on past exploration missions, the surface of Venus contains rocks of different shades of grey, carving out valleys and giving birth to mountains, similar to Earth.

Volcanoes

Both planets feature at least 1,500 active volcanoes on the surface, and many more dormant ones.

10 A PERFECT WORLD FOR FUTURISTIC SPACECRAFT

There are advantages to scrutinising Venus from its clouds

Faster exploration
Super-rotation in the upper atmosphere, which completes a rotation 60 times quicker than the surface below, would allow for rapid exploration of Venus.

Improved capabilities
With lightweight technologies and controlled aerial mobility, aircraft on Venus is now a better proposal than it was in the 1960s.

Head in the clouds
There's discussion about whether it would be possible to create a colony in the clouds of Venus, much like Cloud City on Bespin in the *Star Wars* universe.

Easier to explore from up high
There are more favourable conditions in the clouds, with much more bearable temperatures and pressures.

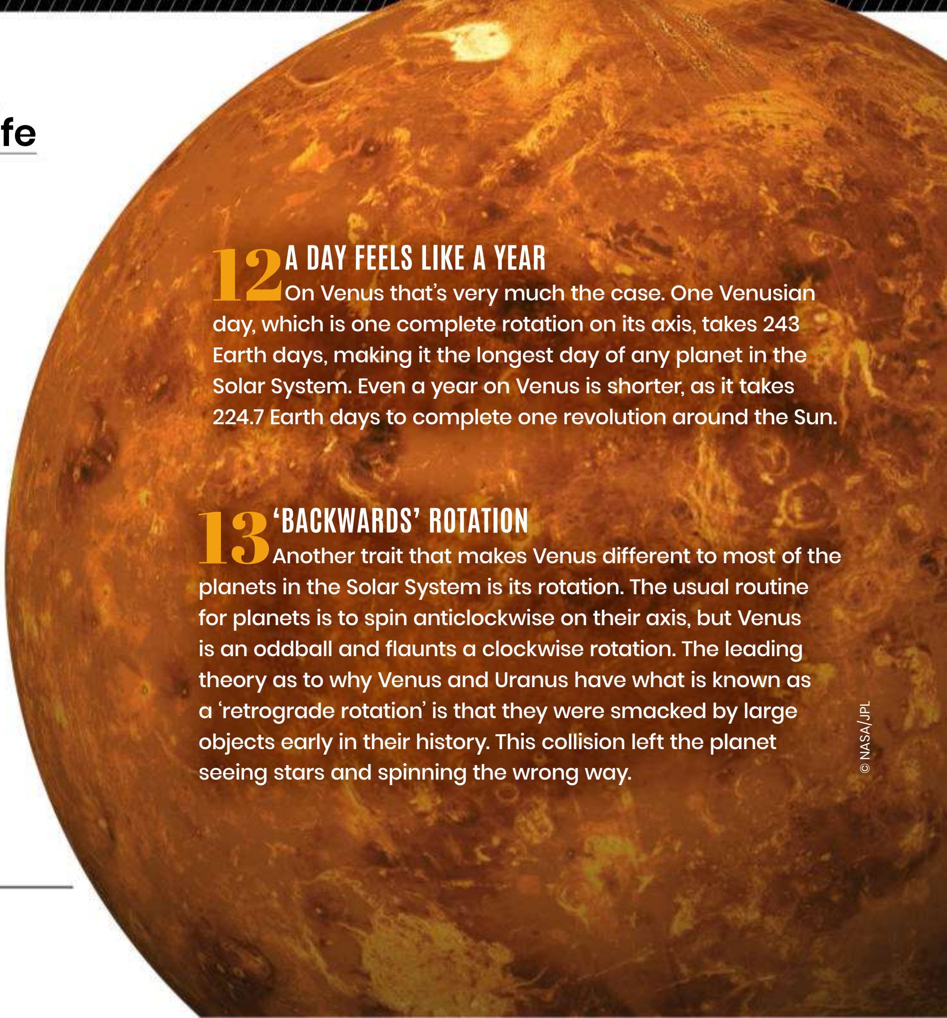
The power of the Sun
Solar panels would be extremely useful, as Venus gets 190 per cent more sunlight than Earth.

Removing obstacles
Being in constant flight eliminates the need to navigate around harmful terrain and the planet's volcanoes.

> "Conditions on Venus that would be favourable for life could exist in the clouds"

11 LIFE IN THE CLOUDS

Researchers have proposed that life could be found on Venus, just not on the surface. A study by Sanjay Limaye of the University of Wisconsin-Madison's Space Science and Engineering Center suggested that microbial life could be present in the cloud tops. Microbial life on Earth has been found at altitudes of 41 kilometres (25 miles), and researchers have said that conditions on Venus that would be favourable for life could exist in the clouds at altitudes of 48 to 51 kilometres (30 to 32 miles). Here, temperatures would be roughly 60 degrees Celsius (140 degrees Fahrenheit) and pressures would be similar to Earth at sea level.



12 A DAY FEELS LIKE A YEAR

On Venus that's very much the case. One Venusian day, which is one complete rotation on its axis, takes 243 Earth days, making it the longest day of any planet in the Solar System. Even a year on Venus is shorter, as it takes 224.7 Earth days to complete one revolution around the Sun.

13 'BACKWARDS' ROTATION

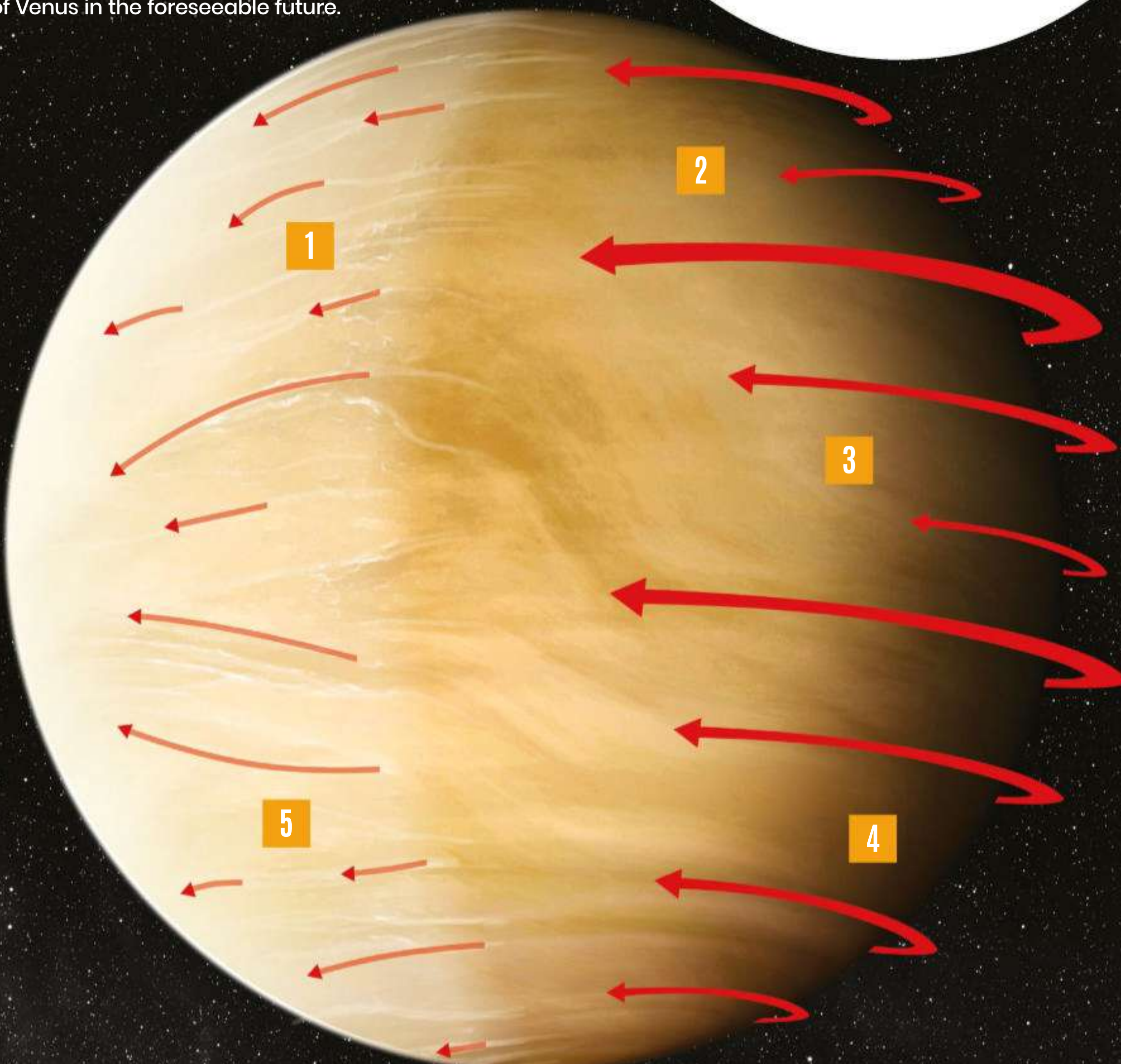
Another trait that makes Venus different to most of the planets in the Solar System is its rotation. The usual routine for planets is to spin anticlockwise on their axis, but Venus is an oddball and flaunts a clockwise rotation. The leading theory as to why Venus and Uranus have what is known as a 'retrograde rotation' is that they were smacked by large objects early in their history. This collision left the planet seeing stars and spinning the wrong way.

14 WHAT THE FUTURE HOLDS

Researchers want to understand every planet in the Solar System. Efforts in the late-20th century showed that Venus is a difficult planet to observe remotely from the surface, but with new technologies and a better understanding comes innovative exploration ideas. A lot of these new ideas have a common theme, which is exploring Venus from within the clouds. As Venus has more favourable conditions in the clouds, with wind speeds that allow an object to travel around the planet much faster than it rotates, scientists are looking to introduce aircraft or airships. By utilising solar and wind power, and with the added help of buoyancy, robotic missions could become a feature of Venus in the foreseeable future.

15 REWINDING THE CLOCK

Much like Mars, Venus could have once supported life. 700 million years ago, Venus suffered dramatic changes in its climate that saw it bulk up its atmosphere in a process known as a 'runaway greenhouse effect'. Before the runaway greenhouse effect took over, it's believed that Venus had a reasonable atmosphere and could have harboured liquid water for about 2 or 3 billion years. Before carbon dioxide dominated the atmosphere and made it too hot and dense, it's possible that Venus had an environment that could have supported life for billions of years.



1 Seen from above

These irregular, patchy, filament-like structures were observed by the European Space Agency's Venus Express spacecraft.

2 Stationary waves

Stationary or gravity waves in the nightside's atmosphere do not move in the same way as the planet's super-rotation.

3 Indirect surface observations

These waves come from steep, mountainous areas on Venus that send waves through the atmosphere.

4 Never-ending heat

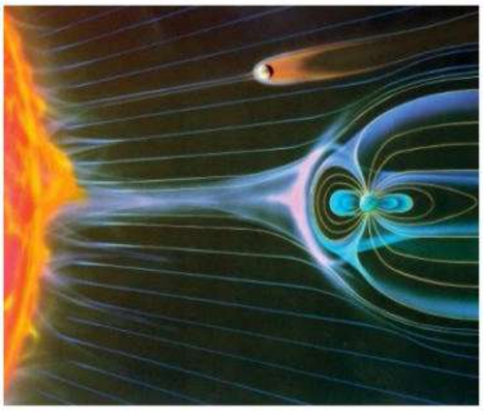
The extremely slow rotation and tilt of just 3.39 degrees ensure that the planet stays continuously hot.

5 The mystery of the nightside

On the nightside the upper clouds form in different shapes and morphologies, causing a more irregular system.

16 TOO SLOW TO BE MAGNETIC

Although it's often referred to as Earth's twin, something that differentiates the two planets deep down to their cores is that Venus creates a negligible magnetic field. Planetary scientists believe that Venus has an iron core that's a similar size to Earth's. However, the sluggish rotation of Venus, which consequently reduces the motion of the planet's core, weakens the planet's magnetic field, or magnetosphere.



17 IT'S HAD MANY SPACECRAFT VISITORS

Before attention turned to the exploration of Mars, Venus was where space agencies wanted to send their robotic missions to. This genesis of interplanetary exploration began with a lot of spacecraft and launch failures, starting with the Soviet Union's Tyazhely Sputnik in February 1961, which experienced a launch failure. There have since been 45 other missions launched with the intention of exploring the planet. Of these missions, more than 20 have been successful. The very first to conduct a successful planetary encounter was NASA's Mariner 2 space probe on 14 December 1962.

18 THE CASE OF THE MISSING LIGHTNING

There are electrical pulses bursting through the heavy atmosphere, but missions to Venus to find them have made things even more confusing. Ground-based telescopes and space probes alike, including the ESA's Venus Express and the Japan Aerospace Exploration Agency's (JAXA) Akatsuki, have had nothing more than some subtle hints about the presence of Venusian lightning. Researchers believe it could still be present, just much more localised and rare, which is why there has been no definitive evidence yet. Or it could be the case that there isn't lightning at all.

19 SOVIET SUCCESS AT VENUS

Before the dissolution of the Soviet Union in 1991, the country was prominent in Venus exploration missions in the 1970s and 1980s. One historic mission that the Soviets conducted was Venera 7 in December 1970, which became the first mission to land on a different planet. Then, in March 1982, the Venera 13 lander managed to survive Venus' extreme temperatures and pressures for an astonishing two hours.

20 BRIGHTEST IN THE SKY

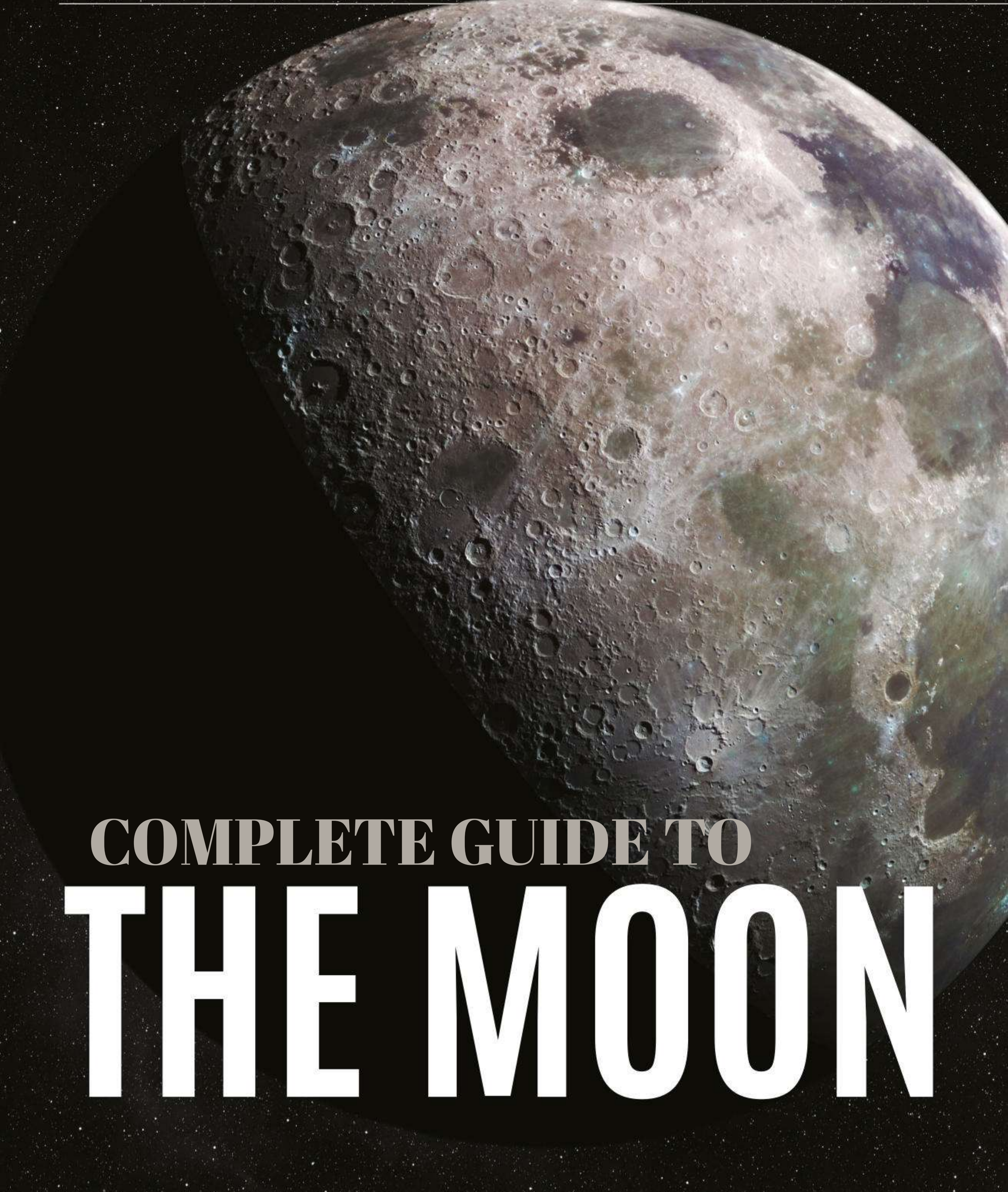
Because Venus is in such close proximity to Earth, it's the third-brightest celestial object in the night sky behind the Sun and Moon. The Latin nickname for Venus, now largely unused, is 'Lucifer', which translates to 'light bringer'. Lucifer is also a name for the devil, which is quite a coincidence considering the hellish conditions on the surface of Venus.

21 A SOURCE OF SHADOWS

As the third-brightest object in the night sky, it's bright enough to cast shadows on Earth. Only two other celestial objects are capable of this: the Sun and Moon. Very good eyesight is needed to see these Venusian shadows.

22 WEIRD WINDS

The clouds move across the atmosphere once every four Earth days, known as super-rotation. This generates speeds of 360 kilometres (224 miles) per hour, surpassing those of the most dangerous hurricanes on Earth. Speeds decrease with cloud height, creating winds that are just a few miles per hour on the surface.



COMPLETE GUIDE TO THE MOON

Even though we know more about our natural satellite than any other celestial body – and have even visited it – the Moon continues to fascinate us

Written by Shanna Freeman

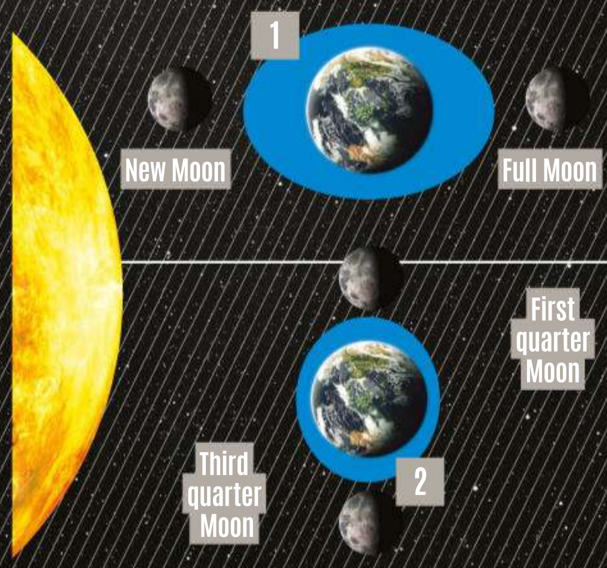
Because we can easily discern features on the Moon with the naked eye, it's been a source of wonder to us since ancient times. The Moon is the brightest object in our sky after the Sun, and influences everything from our oceans to our calendars. It's always been 'the Moon' because we didn't know that there were any others. Once Galileo discovered in 1610 that Jupiter had satellites, we've used the word 'moon' to describe celestial bodies that orbit larger bodies, which orbit stars. Since the Moon has always been so present it might not seem worth studying, yet there's a reason why we continue to return to it – we still have plenty to learn from our satellite.

The Moon is the fifth-largest and second-densest satellite in the Solar System. Its diameter is 27 per cent of Earth's at 3,476 kilometres (2,160 miles), while its mean density is 60 per cent that of Earth's. This makes the Moon the largest satellite in size relative to the planet that it orbits. The Moon is also unusual because its orbit is more closely aligned to the plane of the ecliptic,

"The Moon is the fifth-largest and second-densest satellite in the Solar System"

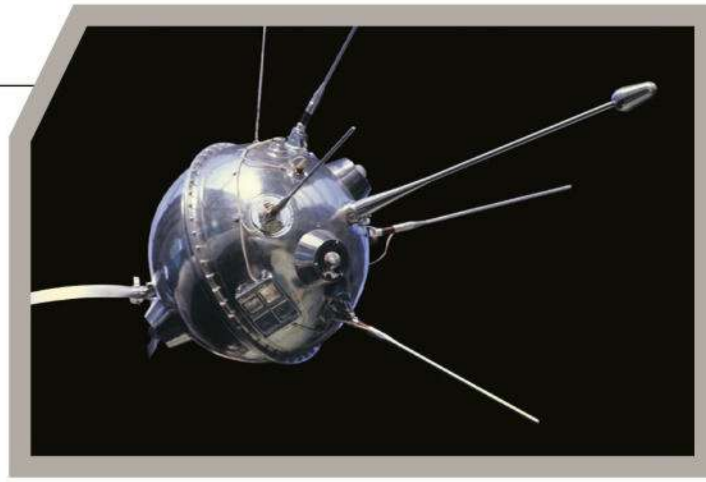
THE MOON AND TIDES

Along with the Sun, the Moon exerts serious force on Earth's tides. Whether the tides vary widely or not much at all has a lot to do with the interactions between the solar and lunar cycles. When they are together, their combined effects produce tidal variations called spring tides – high tides are very high and low tides are very low. If the Sun and Moon are on the opposite sides of the sky, they nullify each others' effects, producing neap tides – with little variation.



1 Spring tide
During new and full Moon, both the Sun and Moon exert a strong effect, producing spring tides.

2 Neap tide
In first and third quarter Moon, the Sun and Moon have little effect on tidal range, leading to neap tides.



the plane in which Earth orbits. Most planetary satellites orbit closer to their planet's equatorial plane, but the Moon is inclined from the plane of the ecliptic by approximately 5.1 degrees.

Its average distance from Earth is 384,400 kilometres (239,000 miles), and it completes an orbit once every 27.3 days. The Moon is in synchronous rotation with Earth – its rotation and orbital period are the same – so the same side is almost always facing our planet. This is called the 'near side' of the Moon, while the opposite side is the 'far' or 'dark' side, although it gets illuminated just as often as the near side. This hasn't always been the case: the Moon used to rotate faster but the influence of Earth caused it to slow and become locked.

Although we say that we can only see one side of the Moon at a time, that's not strictly true. The Moon's orbit isn't quite circular – it has an eccentricity of 0.0549. The Moon also wobbles a bit along its orbit. These two factors cause some variations in how much of the Moon that we see, called librations. When the Moon is closest to Earth, called the perigee, it orbits slightly slower than it rotates. This means that we can actually get a glimpse of about eight degrees of longitude of its eastern far side. When the Moon is at its furthest point away in its orbit, the apogee, its orbit is slightly faster than its rotation. So we get a glimpse of eight degrees of longitude on its western far side. This is called longitudinal libration.

The Moon also appears to rotate towards and away from Earth. This is due to the 5.1-degree inclination of its orbit, as well as the 1.5-degree tilt of the Moon's equator to the plane of the ecliptic. This results in us seeing about 6.5 degrees of latitude on the far side along both the sides of the poles. The Moon's orbit also means that it appears to move about 13 degrees across the sky each day, and this movement accounts for the lunar phases.

The Moon's gravitational pull has a strong effect on Earth. The most obvious effect to us is the tides. High tide occurs when the level of water at the coastline rises, and low tide occurs when the water rushes further out. While some coastlines experience one high tide and one low tide per day, of equal strength, others have different strengths, timing and numbers of tides. Measuring and predicting these tides is vital for everything from fishing to navigating intercoastal waterways. We use the term 'tides' to describe oceanic tides, but tides also occur on a smaller level in lakes as well as Earth's atmosphere and crust.

Scientists believe that the Moon formed when a huge celestial body about the size of Mars – which has been given the name Theia – impacted with a young Earth. This is known as the giant impact hypothesis. This force sent debris out into Earth's orbit, which fused to form the Moon. However, in 2012 an analysis of rock samples taken from the Moon during the Apollo missions showed that the Moon's composition is almost identical to Earth's. This calls the giant impact hypothesis into question because previously we thought that at least some of the Moon's material had to have come from Theia.

MEASURING UP THE MOON BY ITS DIAMETER

Ganymede
Jupiter
5,268 kilometres (3,300 miles)

Titan
Saturn
5,150 kilometres (3,200 miles)

Callisto
Jupiter
4,821 kilometres (3,000 miles)

IO
Jupiter
3,642 kilometres (2,300 miles)

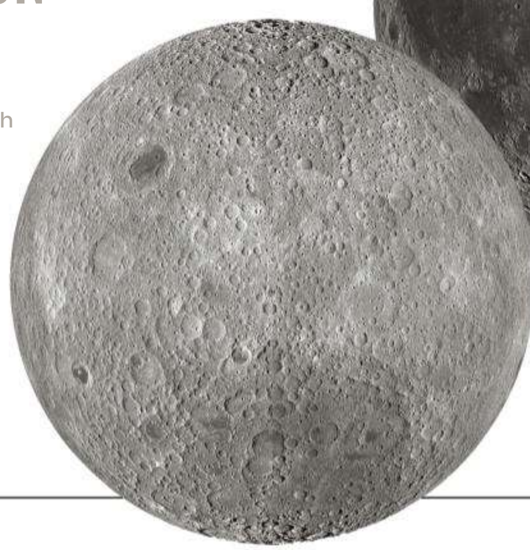
The Moon
Earth
3,476 kilometres (2,160 miles)

Europa
Jupiter
3,122 kilometres (1,940 miles)

Triton
Neptune
2,700 kilometres (1,700 miles)

Titania
Uranus
1,578 kilometres (980 miles)

TWO SIDES OF THE MOON



As opposed to the near side, the far side is covered with craters and very little maria. This may be because it's hotter on that side, or because it experienced a collision.

The near side is mostly covered in dark areas that were originally thought to be seas, called maria. The lighter areas are called the lunar highlands.

HOW THE MOON WAS MADE

1 Theia nears Earth
A Mars-sized object on an unalterable collision course with early Earth.

2 Earth is hit
The impactor hit Earth in a head-on collision, vaporising both Theia and the mantle of Earth.

3 Material is thrown out
The vaporised material from both bodies mixed and was thrown outwards.

4 Debris gathers
Smaller objects began to condense out of the vapour while continuing to orbit around Earth.

5 The Moon takes shape
Many of the smaller objects stuck together to form a protomoon in orbit around Earth.

6 Our companion is formed
Eventually all the pieces came together to form the basis of the Moon we see today.

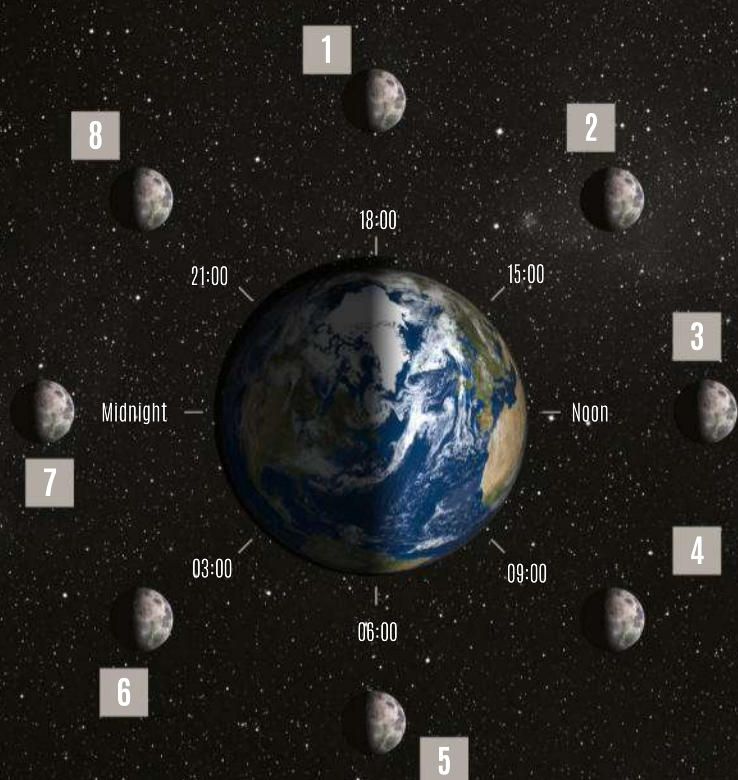
THE MOON'S ORBIT

1 First quarter
Half of the Moon is visible in the afternoon and early evening.

2 Waxing crescent
Up to 49 per cent of the Moon is visible in the afternoon and after dusk.

3 New Moon
The first visible crescent in the southern hemisphere, seen after sunset.

4 Waning crescent
Up to 49 per cent is visible just before dawn and in the morning.



5 Third quarter
Half of the Moon is visible in the late evening and morning.

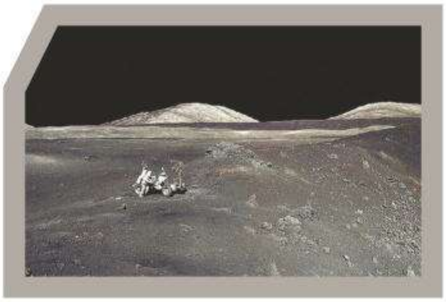
6 Waning gibbous
Between 51 and 99 per cent of the Moon is visible for most of the evening and in the early morning.

7 Full Moon
The entire Moon is visible all night long.

8 Waxing gibbous
Between 51 and 99 per cent is visible in the later afternoon and most of the evening.

INSIDE AND OUT

Earth's natural satellite shares some remarkable similarities with our home planet

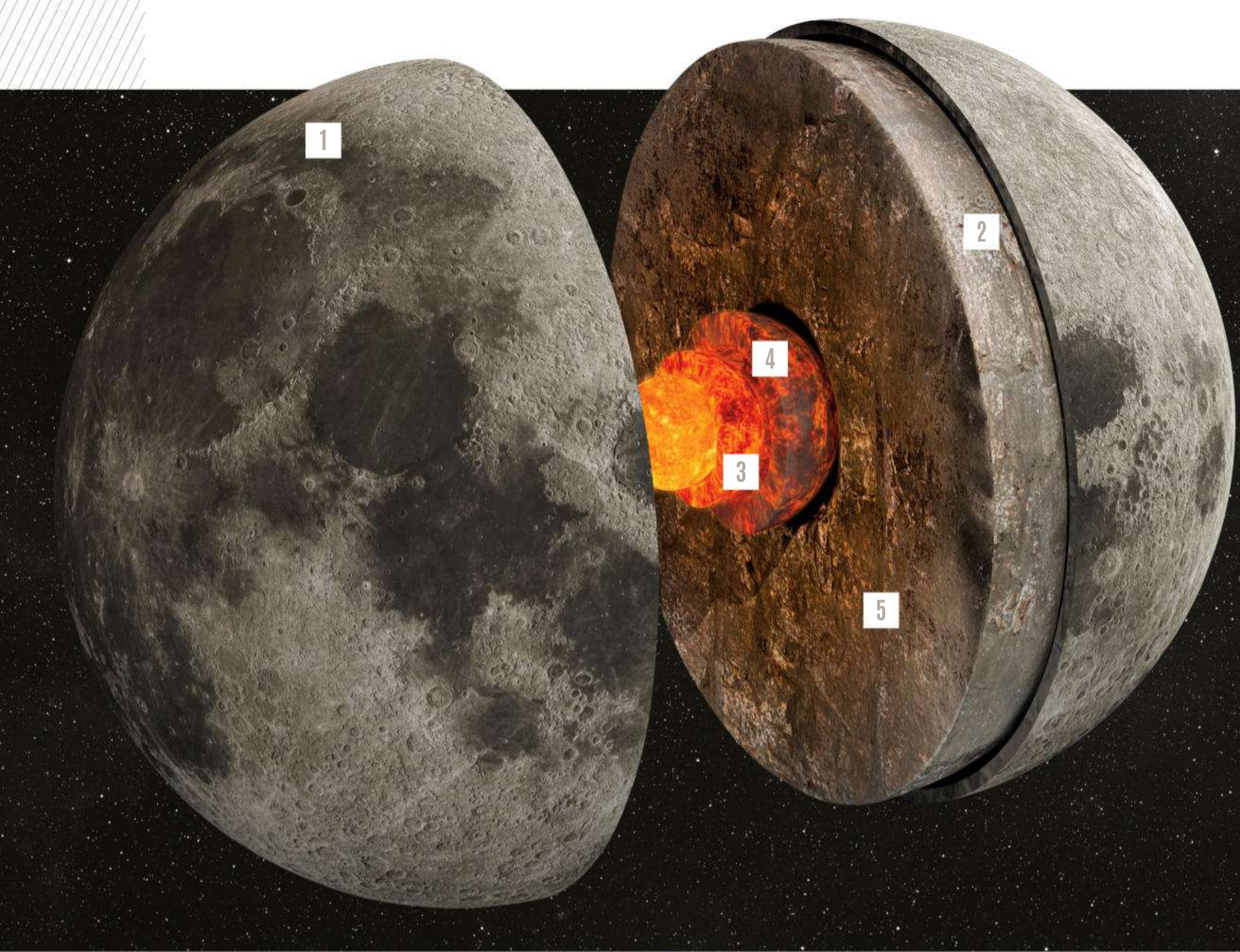


When astronauts explored the Moon they discovered it has moonquakes

Although the Moon may seem like a solid rock, it's actually differentiated like Earth; it has a core, a mantle and a crust. The Moon's structure likely came from the fractional crystallisation of a magma ocean that once covered it. This probably happened not long after the Moon was formed, about 4.5 billion years ago. As the magma ocean cooled, its composition changed as the different minerals within the melt crystallised into solids. The denser materials sank, forming the mantle, while less dense materials floated on top and formed the crust.

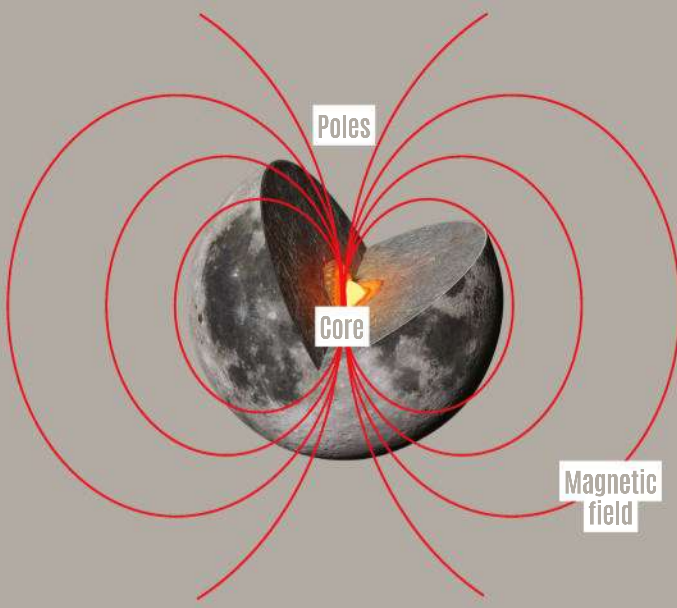
The core is probably very small, with a radius about 20 per cent the total size of the Moon. By contrast, most differentiated celestial bodies have cores about 50 per cent of their total size. The core itself comprises a solid innermost core that is rich in iron as well as nickel and sulphur, with a radius of 240 kilometres (150 miles). This is surrounded by a fluid outer core with about a 300-kilometre (186-mile) radius. Between the core and the mantle, there's a boundary layer of partially melted iron that has about a 500-kilometre (300-mile) radius. It is also known as the lower mantle. The upper mantle is mafic – rich in magnesium and iron, topped by a crust of igneous rock called anorthosite. It mainly includes aluminium, calcium iron, magnesium and oxygen, with traces of other minerals. We estimate the crust is around 50 kilometres (31 miles) thick.

The Moon has no plate tectonics, but it does have seismic activity. When astronauts visited the Moon they discovered that there are moonquakes – the Moon's equivalent of earthquakes. Moonquakes aren't nearly



THE MAGNETIC FIELD MYSTERY

The Moon has an external magnetic field – it's less than one-hundredth that of Earth's magnetic field. It's not a dipolar magnetic field like Earth, which has a field that radiates from the north and south poles. Researchers believe the Moon once had a dipole magnetic field, created by a dynamo – a convecting liquid core of molten metal. But we aren't sure what powered that dynamo. It could have worked like Earth's dynamo. Earth's dynamo powers itself as elemental radioactive decay maintains convection in the core. The Moon could also have had a dynamo powered by the cooling of elements at the core.



THE MOON BY NUMBERS

400

How many times bigger the Sun is than the Moon. It's also about 400 times further away from Earth, which is why they look the same size in the sky

29.5 DAYS

The length of a lunar month, longer than the amount of time it takes the Moon to orbit Earth because Earth is moving, too

12

The number of people who have set foot on the Moon

3.8 CENTIMETRES

The distance the Moon moves away from Earth each year

13 HOURS

The amount of time it takes to reach the Moon by rocket

16.6 KILOGRAMS

The amount you would weigh on the Moon if you weighed 100 kilograms on Earth

1 Crust
The crust is igneous rock called anorthosite, about 50 kilometres (31 miles) thick.

2 Mantle
The main mantle is mafic – rich in magnesium and iron.

3 Inner core
The inner core is rich in iron with a radius of 240 kilometres (150 miles), and much smaller than the cores of most terrestrial bodies.

4 Outer core
The fluid outer core has a 300-kilometre (186-mile) radius.

5 Partial melt
This partially melted layer is mostly iron, with a radius of 500 kilometres (300 miles).

as strong as earthquakes, but they can last longer because there's no water to lessen the effects of the vibrations. Seismometers showed that the strongest moonquakes are about 5.5 on the Richter scale. There are four different types of moonquakes: shallow, deep, thermal and meteorite. Shallow ones occur 20 kilometres (12 miles) below the surface, while deep moonquakes can be as deep as 700 kilometres (435 miles). These deep moonquakes are probably related to stresses on the Moon caused by its eccentric orbit and gravitational interactions between it and Earth. Thermal earthquakes occur when the crust of the Moon heats and expands. Shallow moonquakes are the strongest and most common. Nearly 30 were recorded between 1972 and 1977 by seismometers on the surface. This seismic data has helped us to determine the Moon's internal composition.

The dominating feature on the near side of the Moon's surface, called maria, are the result of ancient volcanic activity. These vast, dark plains are basalts – igneous rock that formed after lava erupted due to partial melting within the mantle. These basalts show that the Moon's mantle is much higher in iron than Earth's, and has a varied composition. Some basalts are very high in titanium, while others are higher in minerals like olivine.

These basalt maria have influenced the Moon's gravitational field because they're so rich in iron. The gravitational field contains mascons, positive gravitational anomalies that influence how spacecraft orbit the Moon. The maria can't explain all of the mascons that have been tracked by the Doppler effect on the radio signals emitted by spacecraft that orbit the Moon. And there are also some large maria without associated mascons.

ON THE SURFACE

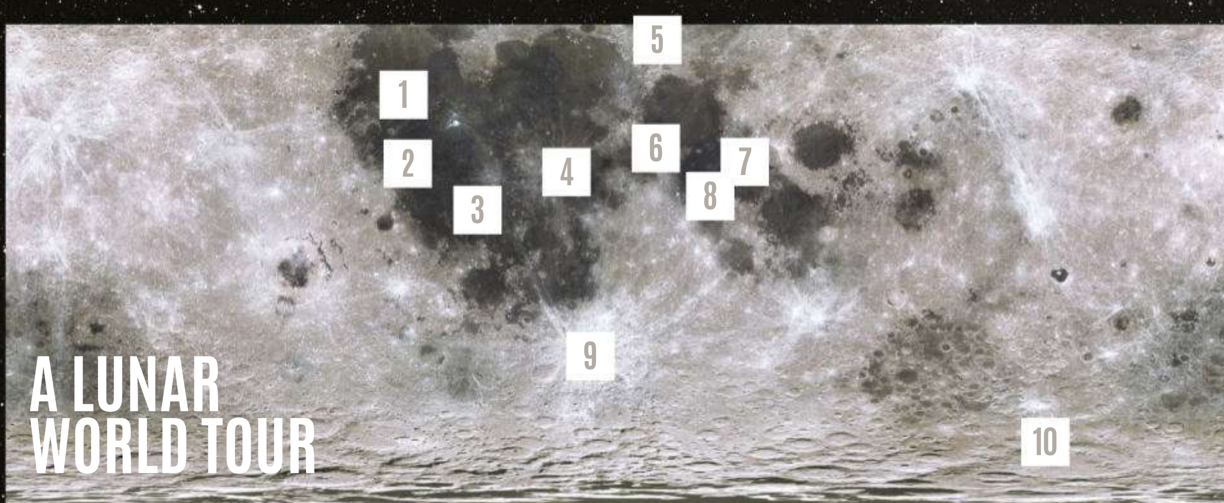
The surface of the Moon is about contrasts: light and dark, hot and cold

The landscape of the Moon is dominated by three main features: maria, terrae and craters. The basalt maria appear dark due to their high iron content and are much more prevalent on the near side of the Moon. Other volcanic features on the surface include domes and rilles. Domes are shield volcanoes that are round and wide with gentle slopes, while rilles are twisting sinuous formations caused by channels of flowing lava.

The lighter areas on the Moon are called terrae, or lunar highlands. They are made up of anorthosite, the type of igneous rock that dominates the overall crust of the Moon. While this type of rock can be located in some places on Earth, it's not generally found on the surface due to plate tectonics and deposits. These highlands reflect light from the Sun and make it appear that the Moon is glowing at night.

Both the maria and terrae have impact craters which were formed when asteroids and comets struck the surface of the Moon. These craters range in size from very tiny to massive. It is estimated that there are

The last manned mission to the Moon took place in December 1972



A LUNAR WORLD TOUR

1 Oceanus Procellarum
This mare is so large that it was deemed an ocean, covering about 4,000,000 square kilometres (1,500,000 square miles).

2 Luna 9
This site marks the first soft landing of an unmanned spacecraft on the Moon, launched by the Soviet space program on 31 January 1966.

3 Surveyor 1
The first American soft Moon landing happened here, launched on 30 May 1966.

4 Copernicus
This crater is well known because it can be easily seen from Earth. It is a younger crater, about 800 million years old, with a prominent system of ejecta rays.

5 Vallis Alpes
This lunar valley bisects a mountain range called the Montes Alpes, and extends 166 kilometres (103 miles).

6 Montes Apenninus
This mountain range is about 600 kilometres (370 miles) long and has peaks up to 5 kilometres (three miles) high.

7 Mare Tranquillitatis
This mare was the landing site for the Apollo 11 spacecraft. It is slightly bluish because it has a high metal content.

8 Apollo 11
Neil Armstrong and Buzz Aldrin became the first men to set foot on the Moon, on 21 July 1969 as part of NASA's Apollo program.

9 Tycho
This distinctive crater has ejecta rays visible from Earth during a full Moon, reaching more than 1,000 kilometres (621 miles) from the crater.

10 Schrödinger
This huge crater near the south pole can only be viewed from orbit. It is 312 kilometres (194 miles) in diameter.

EXPLORING THE MOON: THE PAST

Apollo 11 21 July 1969
NASA astronauts Buzz Aldrin and Neil Armstrong became the first humans to set foot on another body in space when they landed on the Moon in 1969.

Apollo 12 19 November 1969
The second spacecraft to land on the Moon, Apollo 12, used a Doppler effect radar technique to land the spacecraft within walking distance of the Surveyor 3 probe, which had landed on the lunar surface about two years prior.

Apollo 14 5 February 1971
The commander on board the third spacecraft to land on the Moon was Alan Shepard who, a decade earlier on 5 May 1961, had become the second person in space after Yuri Gagarin and the first American as part of the Mercury program.

Apollo 15 30 July 1971
NASA deemed this Moon landing the most successful so far out of its manned missions. It is also known as the first of the longer missions to the Moon, called 'J missions', staying for three days.

Apollo 16 21 April 1972
Apollo 16 was the first spacecraft to land in the highlands on the Moon, which let the astronauts gather older lunar rocks.

Apollo 17 11 December 1972
This last manned mission to the Moon carried the Traverse Gravimeter Experiment, which measured relative gravity at different sites on the Moon.

Luna 1 4 January 1959
This Soviet probe was the first to reach the vicinity of the Moon and the first to break out of geocentric orbit. But it didn't impact the Moon as had originally been planned.

Luna 21 15 January 1973
This Soviet spacecraft landed on the Moon and carried a lunar rover, Lunokhod 2. It performed numerous experiments and sent back more than 80,000 images.

Luna 24 22 August 1976
This was the last of the Luna missions, landing near Mare Crisium to recover samples. It was the last spacecraft to have a soft landing on the Moon until 2013.

around 300,000 craters on the near side of the Moon that are wider than one kilometre (0.62 miles). The largest impact crater, called the South Pole-Aitken Basin, is about 2,500 kilometres (1,550 miles) in diameter and 13 kilometres (eight miles) deep. The biggest craters also tend to be the oldest, and many are covered in smaller craters. Younger craters have more sharply defined edges, while older ones are often softer and rounder. If the impact was especially large, material may be ejected from the surface to form secondary craters.

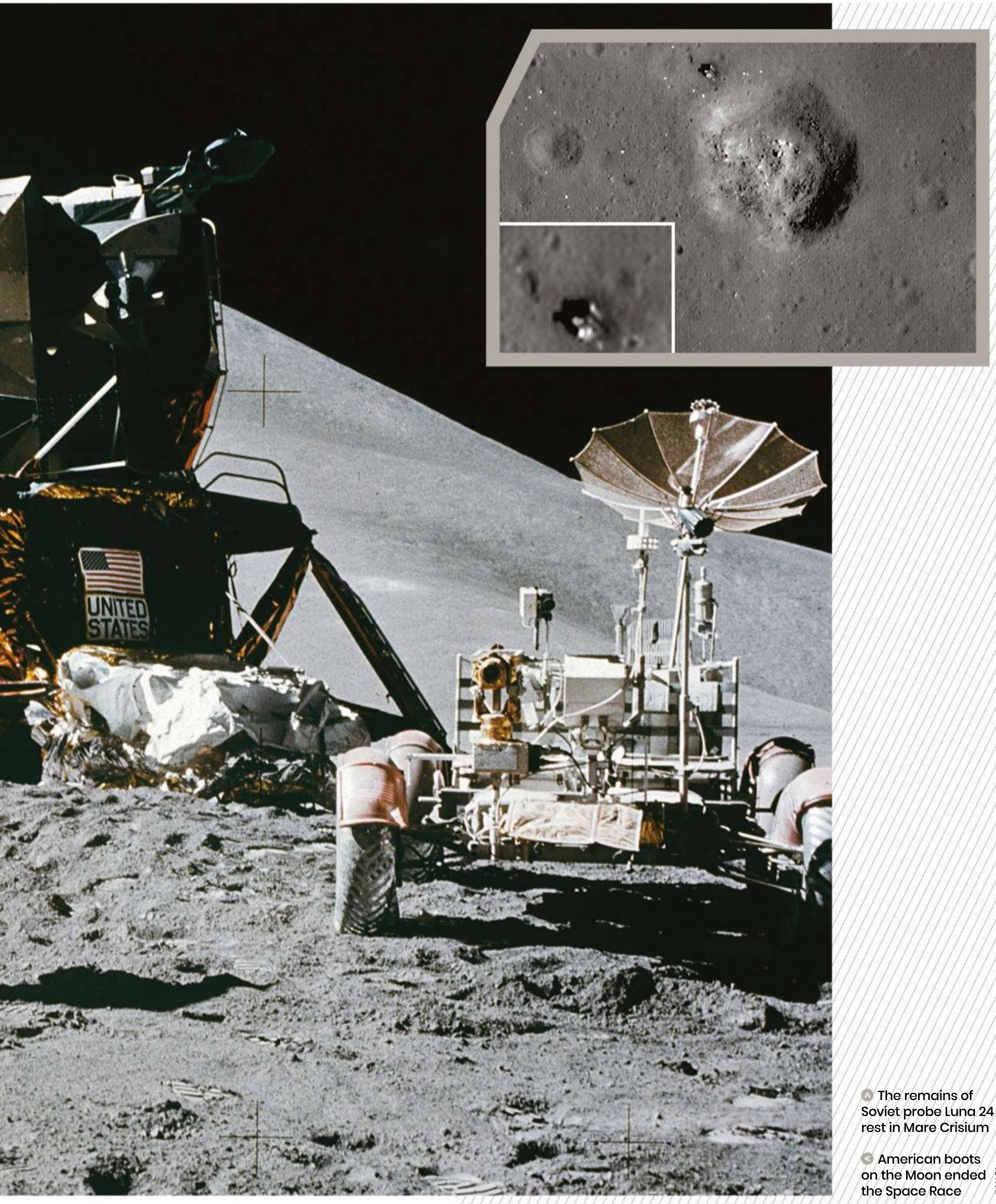
In some cases, the basalt eruptions flowed into or over large impact craters called basins. In general, the terrae have far more craters because the maria are younger in age than the terrae. While the Moon isn't much younger than Earth, our planet has processes that continue to change its surface over time, like erosion and plate tectonics. The Moon doesn't experience these, which is why some impact craters are up to 500 million years older than the basalt filling them.

The loose soil on the Moon is called regolith. It's powdery and filled with small rocks. Over time, impacts from meteors, as well as space weathering (solar wind, cosmic rays, meteorite bombardment and other processes), break down the rocks and grind them into dust. Aside from the basalt and anorthosite rocks, there are also impact breccias – rock fragments that were welded together by meteor impacts – and glass globules from volcanic activity.

Although you may sometimes see the term 'lunar atmosphere', the Moon is actually considered to exist in a vacuum. There are particles suspended above the surface, but the density of the Moon's atmosphere is less than one hundred trillionth that of Earth's atmosphere. What little atmosphere there is gets quickly lost to outer space, and is constantly replenished. Two processes help to replenish the Moon's atmosphere: sputtering and outgassing. Sputtering occurs when sunlight, solar wind and meteors bombard the surface and eject particles. Outgassing comes from the radioactive decay of minerals in the crust and mantles, which can release gases like radon.

The Moon has a very minor axial tilt, so there aren't seasons in the same way that we have them here on Earth. However, temperatures on the Moon can change dramatically because there's no atmosphere to trap heat, and portions of the Moon may be either in full sunlight or total darkness depending on where it is in its rotation. Full sunlight can mean temperatures of greater than 100 degrees Celsius (212 degrees Fahrenheit). But at the end of the lunar day the temperature can drop by hundreds of degrees. There are also big differences in temperatures depending on the surface features. For example, the Moon is coldest in its deepest craters, which always remain in darkness. The coldest temperature ever recorded in the Solar System by a spacecraft was measured by the Lunar Reconnaissance Orbiter in the Hermite Crater near the Moon's north pole at -248 degrees Celsius (-414 degrees Fahrenheit).

"Analysis of rock samples taken from the Moon during the Apollo missions showed that the Moon's composition is almost identical to Earth's"



The remains of Soviet probe Luna 24 rest in Mare Crisium

American boots on the Moon ended the Space Race

© NASA

EXPLORING THE MOON: PRESENT AND FUTURE

We've been studying the Moon for over 50 years, and thanks to a host of pioneering missions we now know more about our satellite than ever before

Although there hasn't been a manned mission to the Moon since 1972 and there were no soft landings at all until 1966, we're still exploring our satellite. Currently the Lunar Reconnaissance Orbiter (LRO) is still circling the Moon. It launched on 18 June 2009, and became the first NASA mission to the Moon in more than a decade. The LRO is meant to be a precursor to future manned missions, and was originally designed to spend just a year in orbit. However, the mission was extended several times. It was designed to extensively map the Moon in high resolution, explore the potential of ice in the polar regions, study the deep space radiation, and continue to map the surface of the Moon. The other current NASA mission is ARTEMIS, an extension of an earlier satellite mission. Two small probes have been orbiting the Moon together since summer 2011, having previously performed lunar and Earth flybys.

The Lunar Crater Observation and Sensing Satellite (LCROSS) was launched along with the LRO and considered an inexpensive way to look for water ice, and it was successful. The LCROSS discovered ice in the Cabeus crater near the Moon's south pole after its upper stage impacted as planned on 9 October 2009. Two small spacecraft under the name GRAIL A and GRAIL B were launched on 10 September 2011 and impacted on 17 December 2012, having collected data to help understand how terrestrial planets have evolved. Japan, India and China have all had lunar probes in the last six years as well.

Humans will return to the Moon in 2025 and explore sites for a permanent base

EARTH TO THE MOON

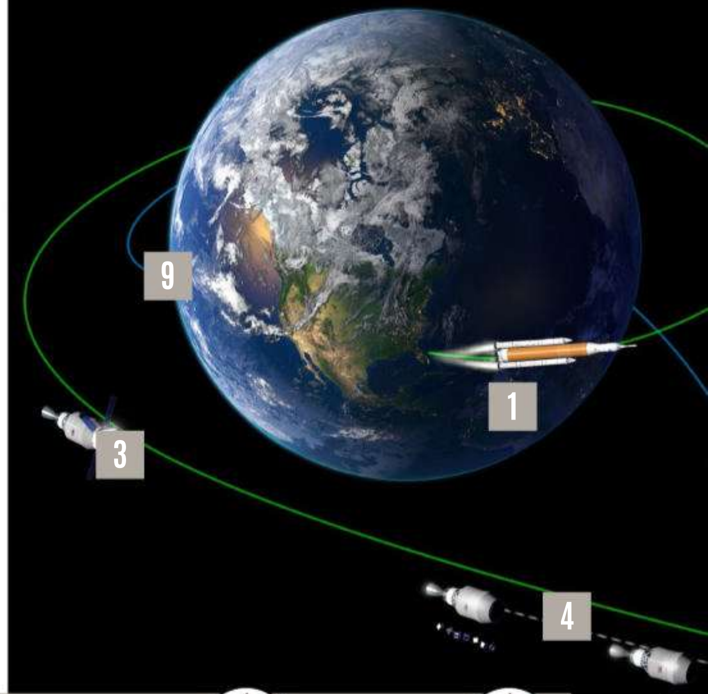
Jump on board the Orion as we follow the route planned for the Artemis astronauts

1 Launch day

Scheduled to launch in 2025, the third Artemis mission and second with crew on board will launch from the Kennedy Space Center in Florida. It will be monitored by the nearby Launch Control Center.

2 Entering orbit

Once the rocket has taken Orion into orbit, its engines shut down and it will separate from the capsule. These rocket components will fall towards the Pacific Ocean. Orion will then deploy its solar arrays.



2022 Artemis I

The first mission will be uncrewed to test the takeoff and the capsule's ability to orbit, descend and splashdown. It will carry 13 small satellites to perform experiments and technology demonstrations. The craft will orbit the Moon for six days, collecting performance data.

2024 Artemis II

Carrying the first four Artemis astronauts, the Orion capsule will take the crew farther from Earth than humans have ever travelled before. Over the approximately ten-day mission, the crew will complete a lunar flyby and return to Earth, evaluating the performance of the spacecraft's systems.

2025 Artemis III

This will see the next man and first woman step onto the lunar surface. Providing previous missions have been successful, the astronauts will shoot towards the Moon, using the lunar lander to lower two people to the south polar region. They will remain on the Moon for around a week.

3 Trans-lunar injection

Having made it into Earth orbit, the Orion vehicle will head to the Moon. During a 20-minute burn, the engines will fire to increase the speed, displacing the spacecraft from its low-Earth orbit.

4 To deep space

Set on a precise trajectory, Orion will travel over 384,000 kilometres (239 miles). This needs to account for factors such as gravity and the movement of the Moon. Artemis I will have tested the planned path.

5 Lunar flyby

A main engine burn 185 kilometres (115 miles) above the Moon's surface will put Orion on a trajectory to intercept the orbit of the planned Lunar Gateway space station, set to launch in November 2024.

6 Moon landing

Having docked with Gateway, the crew may need to inspect it and collect supplies. While two astronauts will stay aboard the spacecraft in orbit, the other two will transfer to a lander vehicle.

7 Lunar exploration

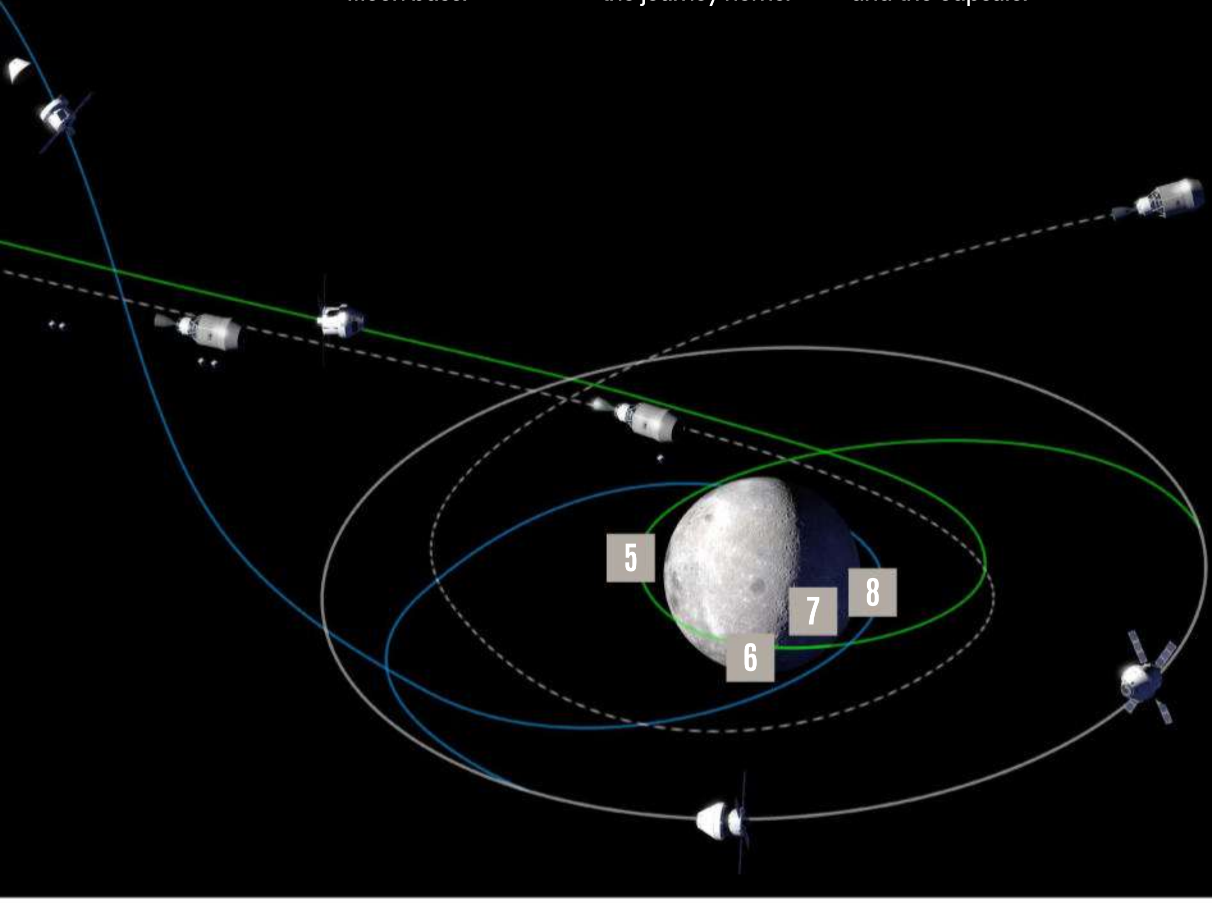
The astronauts will remain on the Moon for roughly seven days. As an area where water ice is present, they will explore the suitability of the lunar south pole for a permanent Moon base.

8 Ascent

Having carried out experiments on the Moon, the astronauts will reboard the Human Landing System and return to Gateway. Taking samples with them, they will return to Orion for the journey home.

9 Splashdown

After spending less than 30 days in space, the parachuted capsule will return to Earth, splashing down in the Pacific Ocean. NASA will have a team ready to retrieve the crew and the capsule.



MAIN MISSION OBJECTIVES

Long-term presence

Following Apollo 17's three-day presence on the Moon, Artemis will send astronauts there for weeks.

Equality

A female astronaut hasn't set foot on the Moon yet. This mission will demonstrate the increasing role women have played in space missions since the Apollo era.

Partnerships

NASA has collaborated with private companies such as SpaceX and Boeing. These show space travel's shift towards commercialisation.

Technology

NASA is always learning from past missions; the spacecraft and spacesuits have been tailored to the Moon mission, exhibiting the latest in space technology.

Knowledge

Collecting further information about the lunar surface and deep space, NASA hopes to become better prepared for later missions back to the Moon and further afield.

Resources

Access to the lunar surface provides the opportunity to search for rare minerals and exploit resources. Hydrogen and oxygen could be used as rocket fuel to travel from the Moon.

Mars was much more Earth-like before its atmosphere was lost

FOCUS ON

WATER ON MARS

China's rover suggests the liquid may have been on Mars much more recently than scientists thought

Reported by Andrew Jones

Evidence is growing that Mars, now cold and dry, had liquid water running on its surface much more recently than previously thought. Scientists have long believed that Mars was wet around 3 billion years ago, during the planet's Hesperian period, then lost much of its water. But a new study presents evidence of water activity from just 700 million years ago, well into the current Amazonian period, posing a new puzzle to crack about the Red Planet and its history.

The new study is based on data from China's Zhurong rover, part of the Tianwen-1 mission that touched down on the surface of Mars in May 2021. In particular, the scientists used data the rover gathered during its first 92 Martian days, or sols, at its landing site in Utopia Planitia. Yang Liu, a researcher at the National Space Science Center (NSSC) under the Chinese Academy of Sciences (CAS), and colleagues analysed data from three different instruments on Zhurong: the laser-induced breakdown spectrometer, the telescopic microimaging camera and the short-wave infrared spectrometer.

Those instruments studied minerals that suggest the presence of a substantial quantity of liquid water at the site about 700 million years ago, which scientists previously thought was dry. "This is a very interesting result," says Eva Scheller, a planetary scientist at the California Institute of Technology who wasn't involved

> "It means that particular forms of water-bearing minerals would have formed at much later time periods than have previously been considered"
> **Eva Scheller**

in the new research. "We have very little recorded evidence of 'young' liquid water systems on Mars. And for the ones we have, they were usually in the form of salt minerals." But Zhurong's instruments spotted water molecules locked away in the rock, "which is very interesting and different from other young liquid water environments that have been observed," Scheller explained. "It means that particular forms of water-bearing minerals would have formed at much later time periods than have previously been considered in other scientific studies."

NASA has so far sent its Mars rovers to ancient landing sites, dating back to the Noachian age more than 3.7 billion years ago. Zhurong is not just an extra set of wheels on Mars, but a powerful suite of instruments exploring a new, geologically young site to open new windows of opportunity for research on Mars.

"One of the major things we'll have to find out and that I look forward to seeing from the Zhurong rover is how extensive these 'young' water-bearing minerals are," Scheller said. "Are they common or uncommon in these 'young' rocks?" Zhurong has now covered about two kilometres (1.24 miles) during its more than 350 Martian days and has analysed a range of features on its travels, meaning more new Martian insights are likely still to come from the rover.

LAYERS OF THE RED PLANET

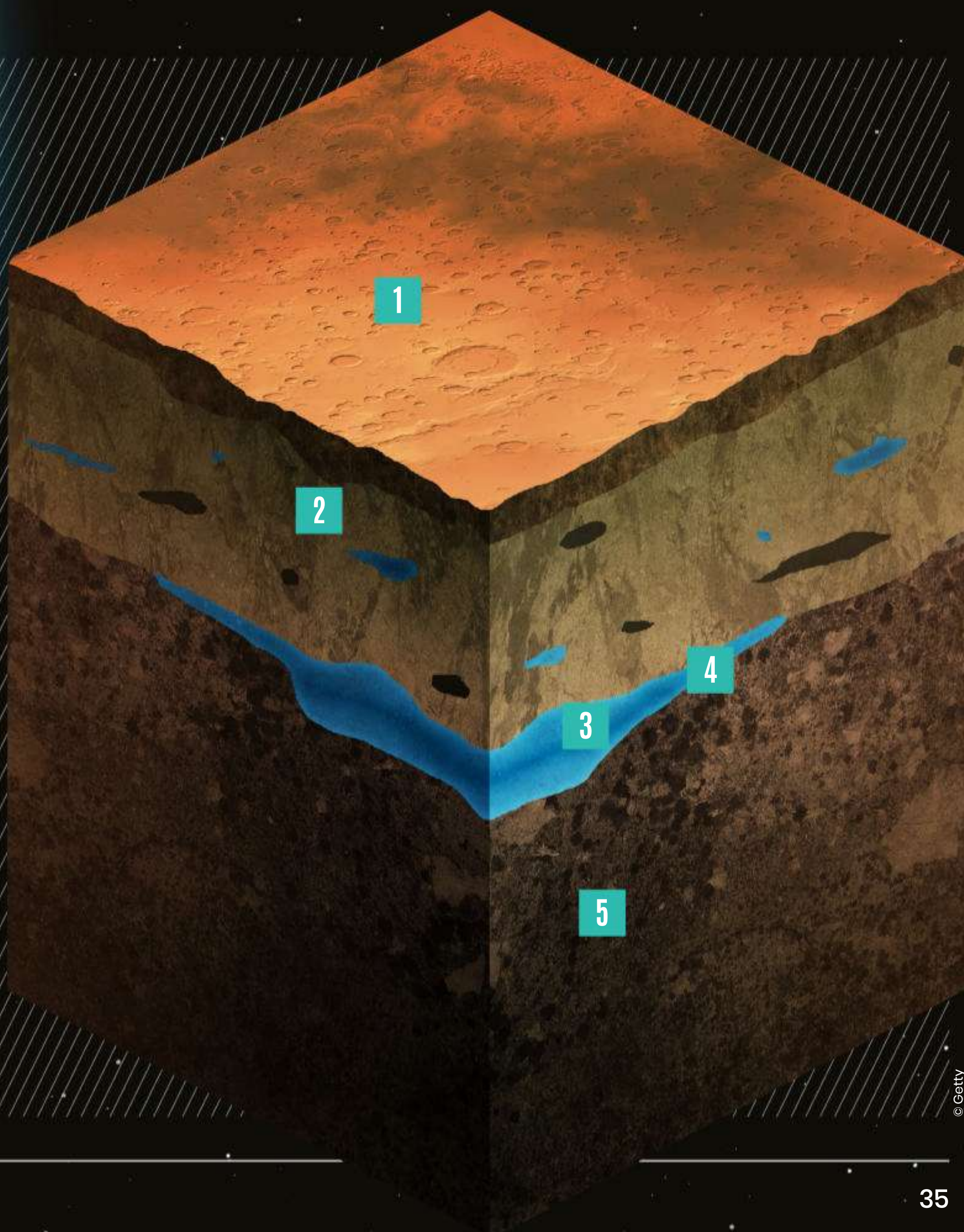
1 Dry soil Martian soil forms a dusty layer. It's made up of nutrients such as sodium, potassium, chloride and magnesium.

2 Signs of ice Surface ice is thought to have become buried, leaving a permafrost subsurface with young ice in its pores.

3 Pockets of water Water ice is locked within cavities across the mid-latitudes of the planet. Some chunks of frozen water have been found just beneath the surface.

4 Subsurface reservoirs Lakes are thought to exist far beneath the surface. A high level of salt or heat from Mars' interior could even result in them being liquid.

5 The foundation The water would lie above an impermeable bedrock, with a high concentration of sulphur.



IS JUPITER PROTECTING US?

Earth has good reason to be grateful to the king of the Solar System, though its influence isn't always benign

Reported by Andrew May

Jupiter is by far the largest planet in the Solar System, containing more than twice as much mass as the rest of the planets put together. As such, its influence on the dynamics of the Solar System is second only to the Sun itself, and it's often said that Jupiter is the planetary 'protector' of Earth. But is that true, and if so, how does it work? To start with, Jupiter isn't really that close to us. The distance from Earth to the Sun is one astronomical unit (AU), while that between the Sun and Jupiter is much bigger at around 5.2 AU. This means that Jupiter never gets closer to us than 4.2 AU, and it's often much further away than that. And as big as Jupiter is, it still only has a thousandth of the Sun's mass, so its direct gravitational effect on us is negligible in comparison.

The reality is that Jupiter's influence on Earth isn't direct, but comes about via its effect on much smaller objects in the Solar System, all the way from asteroids down to grains of dust. Continuously through its 4.6 billion years of existence, Jupiter has helped to shape the Solar System through its gravitational effects. As far as Earth is concerned, we can thank Jupiter for protecting our planet from devastating collisions in the period immediately after its birth and then giving it enough water to fill the oceans. Then it tidied up the surrounding environment by sweeping up a large

© NASA

proportion of the rocky debris left over from planet formation, and even today it continues to shepherd incoming comets away from the inner Solar System.

To look at all of that in a little more detail, we need to go right back to the dawn of the Solar System. According to current theories – based largely on computer modelling – it's quite possible that Earth wouldn't exist at all if wasn't for Jupiter. One view that's popular with astronomers is the so-called 'grand tack' model, originating from 2011. The name comes from a sailing analogy, as one of its originators, Kevin Walsh of the Southwest Research Institute in Boulder, Colorado, explained at the time: "We refer to Jupiter's path as the grand tack because the big theme in this work is Jupiter migrating towards the Sun and then stopping, turning around and migrating back outwards. This change in direction is like the course that a sailboat takes when it tacks around a buoy."

In the grand tack hypothesis, Jupiter was the first planet to form, but it did so significantly closer to the Sun than it is today, at about two-thirds of its present distance. Then, almost immediately, its orbit started to change. The entire space around the Sun was still filled with a relatively dense disc of gas and dust that sapped energy from the newly created planet through a process analogous to aerodynamic drag. This caused Jupiter to spiral into an even smaller orbit, only stopping after the formation of a second planet, Saturn. Orbiting further out than Jupiter, Saturn pulled it back outwards until Jupiter ended up close to its present position. This whole process took around half a million years – a very short period by astronomical standards – and was over before Earth and its neighbouring inner planets had even begun to form. But their destinies had been sealed. Jupiter's inward plunge pushed large quantities of rocky debris, which might otherwise have coalesced into a gigantic inner planet, into the Sun. This left just enough material to make Mercury, Venus, Mars and Earth – the latter at just the right distance from the Sun to provide surface temperatures in the narrow range where the development of life was possible.

Of course, the emergence of life on Earth required other factors besides the

"As far as Earth is concerned, we can thank Jupiter for protecting our planet from devastating collisions"

JUPITER AND THE ASTEROID BELT

If the Solar System had evolved slightly differently, life on Earth might not exist

1 Disrupted asteroid belt

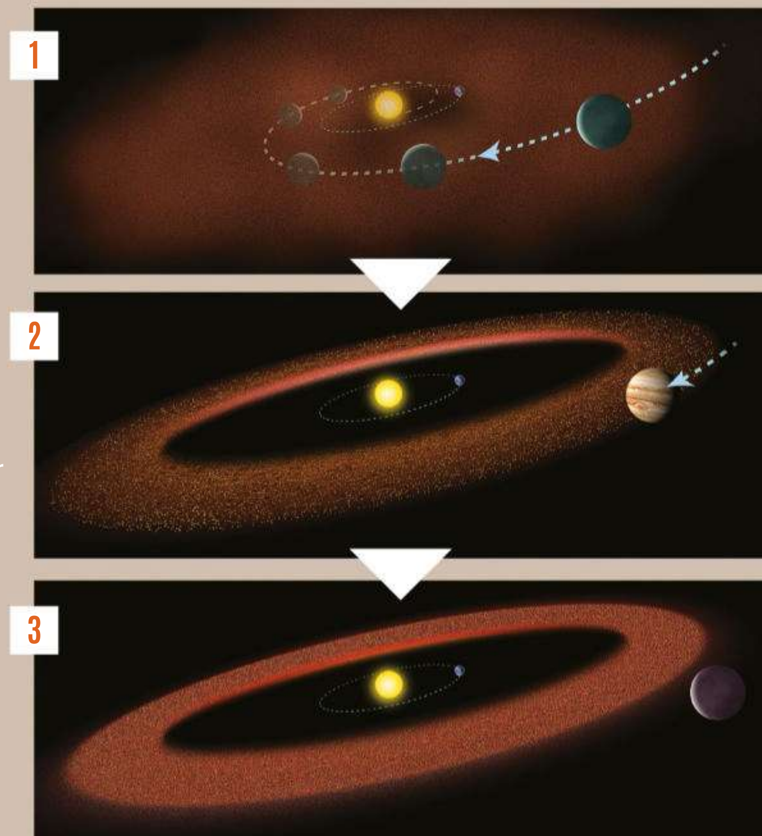
If Jupiter's inward migration had continued all the way through the asteroid belt, it would have disrupted Earth's development so much that it would probably have prevented the emergence of life here.

2 Solar System asteroid belt

This shows what actually happened in the Solar System. Although Jupiter did migrate inwards, it stopped outside the main asteroid belt. This allowed the planets further in – Mars, Earth and Venus – to remain stable and undisrupted.

3 Dense asteroid Belt

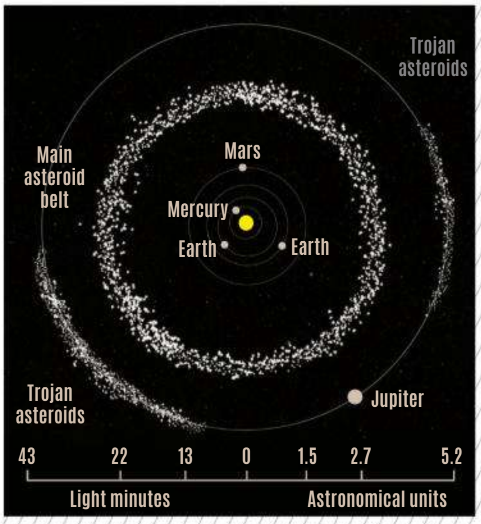
If Jupiter hadn't migrated inwards at all, far more asteroids would have survived to form a much denser belt. Constant bombardment of the inner planets by these asteroids would probably have prevented life from evolving.



WHY WE NEED COMPUTER MODELS

There's no simple solution to the interaction of three or more bodies

The motion of one body orbiting another, such as a lone planet around a star, has an exact mathematical solution. But that's not true if other gravitational effects are involved, such as the influence of Jupiter on the orbit of an asteroid. A few stable solutions can be found algebraically, such as the existence of the 'trojan points' in the orbit of Jupiter itself, but more general solutions require computer modelling on a case-by-case basis. These solutions are not always stable – they may change slowly over the course of many orbits. For example, Jupiter can disturb the orbit of an asteroid that initially comes nowhere near an inner planet into one that poses a collision threat to it.



Some systems, such as TRAPPIST-1, contain no Jupiter-sized planets

Jupiter may actually increase the chances of an asteroid colliding with Earth

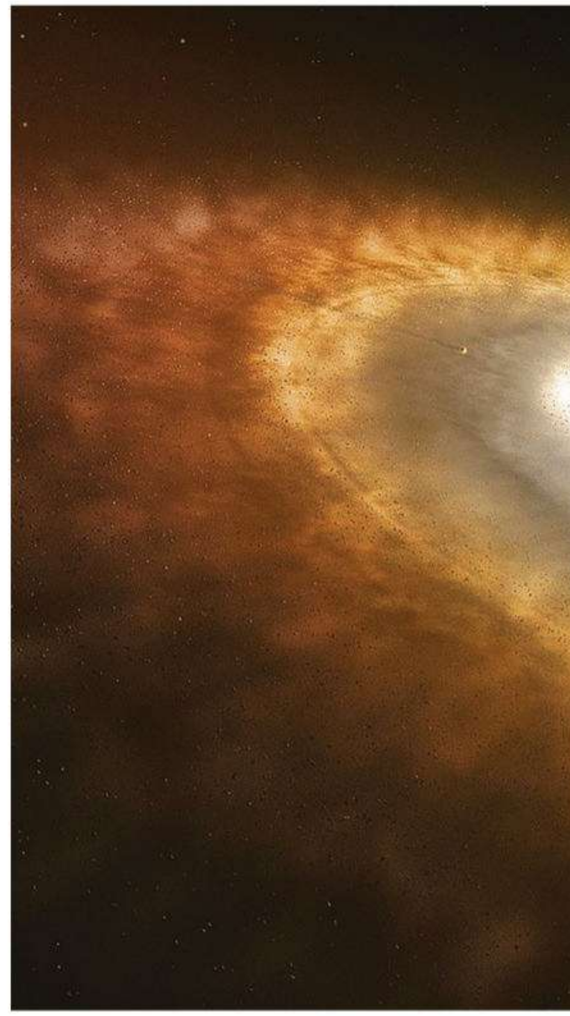
right temperature – perhaps the most important of them being copious amounts of surface water. And it's likely we have Jupiter to thank for this, too. If we're going to call that giant planet our 'protector', it's at this point the concept becomes a little less straightforward. Not too long after the formation of Earth and its rocky neighbours, Jupiter's gravity caused the small planets to be inundated with a heavy rain of debris that it diverted inwards from the outskirts of the Solar System. This might not sound much like protection, but it was certainly a benevolent act from our point of view. That debris consisted largely of ice rather than rock, and it's where most of Earth's water came from.

From our point of view, this may be Jupiter's most important role in our past, and something that could happen in any system with a massive Jupiter-like planet orbiting out beyond rocky inner planets. As David O'Brien of the Planetary Science Institute said in 2018: "I think the coolest thing is that it basically implies for any exosolar system where you

OTHER PLANETARY SYSTEMS

Astronomers have observed many systems without a Jupiter equivalent, and they don't have an Earth either

It's tempting to think that our Solar System is typical, with the giant planet Jupiter relatively far from the host star, while Earth and other rocky planets are further in, and nothing is closer to the Sun than Mercury. But as NASA researcher Yasuhiro Hasegawa observed in 2020, "that kind of configuration currently seems very rare". In fact, many exoplanet systems seem to lack anything resembling Jupiter, while so called super-Earths – planets larger than Earth that are much closer to their star than Mercury is to the Sun – appear quite common. It's possible that such a super-Earth did start to form early in the life of the Solar System, but was then pulled to pieces by Jupiter's gravity during the grand tack, with most of the debris falling into the Sun. This left just enough material for Earth to form, so it's yet another reason for us to be grateful to Jupiter.



have giant planets and terrestrial planets, those giant planets would send water inward to the terrestrial planets." As far as the Solar System is concerned, these large-scale cometary bombardments lie billions of years in the past, but there is evidence that similar things are happening in younger planetary systems today. In 2022, for example, NASA reported observations by its Spitzer Space Telescope that appear to show an ongoing comet storm around the young star Eta Corvi.

In our Solar System, Jupiter has shepherded most of the remaining protoplanetary debris into a neat ring – the asteroid belt – between its own orbit and that of Mars. This contains over a million objects that are large enough to be seen through telescopes from Earth, but most of them are little more than boulder-sized, with a combined mass less than that of Earth's Moon.

As far as Earth is concerned, Jupiter's role today is pretty much a 50:50 balance between protective and destructive. In the latter category, Jupiter's gravity can sometimes nudge an asteroid out of its neat orbit in the asteroid belt and cause it to fall inwards towards the Sun, where there's a chance – though not necessarily a big one – that it might collide with Earth. On the other side of the scale, Jupiter's most protective effect relates to so-called long-period comets, which fall in from the Oort Cloud that lies on the outermost periphery of the Solar System. These are often much larger than the more familiar short-period comets, and generally travel at very high speeds when they arrive. They're potentially pretty dangerous, but fortunately Jupiter's gravity tends to swing most of them back out of the Solar System before they get anywhere near Earth. Without Jupiter acting as gatekeeper in this way, it's likely that long-period comets would hit Earth much more frequently than they do.

So is Jupiter Earth's protector or not? If we take a narrow view at the present time it's not an easy question to answer, though it seems to be doing a reasonably good job of keeping us out of harm's way. But if we take a longer look, all the way back to the very beginnings of the Solar System, we can safely say we wouldn't be here at all if it wasn't for Jupiter.

Andrew May
Space science writer
Andrew has a PhD in astrophysics and 30 years in public and private industry. He enjoys space writing and is the author of several books.

Artist's impression of a newly formed star surrounded by a dusty disc prior to planet formation

Artist's conception of a storm of comets around the young star Eta Corvi

JUPITER AND COMETS

Jupiter can change orbits, making a comet either more or less likely to hit Earth

As comets fall inwards towards the Sun on highly elongated orbits, they may feel enough of a pull from Jupiter's gravity to alter their course significantly. This has happened several times to comet 67P/Churyumov–Gerasimenko, best known as the destination of the Rosetta mission in 2014. Over the course of multiple orbits between 1840 and 1959, its closest approach to the Sun gradually reduced from 4.0 to 1.3 AU – the latter close enough to Earth's own orbit to be worrying if the inward trend resumes in future. But Jupiter can also have a protective effect by swallowing up comets that get too close to it, as was seen in dramatic fashion in 1994 when the fragments of Comet Shoemaker-Levy 9, already broken apart by Jupiter's gravity, crashed one after another into the giant planet.

JUPITER THE DESTROYER?

As beneficial as Jupiter is to Earth, it also has a destructive side

Using computer simulations, Dr Jonti Horner of the University of Southern Queensland in Australia examined how the presence of Jupiter affects the rate of impacts on Earth for three different types of objects: asteroids, short-period comets and long-period comets. He found that only in the last case was Jupiter's effect unambiguously beneficial. For asteroids and short-period comets, on the other hand, Jupiter's presence appeared to increase the collision rate. However, this was relative to the complete absence of a planet-sized object in Jupiter's orbit, which isn't necessarily realistic. In models where there is a planet there, but significantly smaller than the real Jupiter, the rate of collisions turned out to be enormous. Jupiter may not be the best-case scenario, but it's not the worst either.

FOCUS ON

COMETS FADE NEAR SATURN'S ORBIT

It's not just about the Sun's heat

Reported by Elizabeth Howell

When comets first appear near Earth, their bright tails of ionised gas stun observers, but on every return they become dimmer. Astronomers believed that these objects become dimmer on return because they released too much ice and gas during earlier visits to the inner Solar System. The comets melted and shrank because of the Sun's warmth, so when they return there's less material left to release, and therefore a fainter coma. But a new study by scientists from the University of Oklahoma found that even comets that only skirt the inner Solar System and remain beyond the orbit of Saturn fade over time. That makes no sense as in those far reaches of the Solar System, the Sun's light is so weak that it shouldn't be able to melt a comet's ice.

There must be something going on that changes the physical properties of those comets and leads to their fading. The researchers came to this conclusion when they ran computer simulations of comets travelling through the outer Solar System. Models showed that the powerful gravity of Jupiter and Saturn alters the comets' orbits. The comets may have started their journey following highly eccentric elliptical orbits, approaching from the farthest regions of the Solar System far beyond the orbit of Neptune then hurtling towards the Sun before disappearing back into the outer reaches for centuries. But with every passage near Jupiter and Saturn the comets' orbits become more circular, so they don't retreat as far from the Sun.

"We should expect that the outer Solar System has many more comets on these shrunken orbits compared to those on larger orbits," said Nathan Kaib, an associate professor of astronomy at the University of Oklahoma and lead scientist of the new research. The only problem is that those results don't match what astronomers actually see. "Instead astronomers see the opposite," Kaib said. "Distant comets with shrunken orbits are almost entirely absent from astronomers' observations, and comets with larger orbits dominate our census of the outer Solar System."

To explain this strange absence, the researchers posit that the comets must have faded. Even though they are there, somewhere beyond the orbit of Saturn,

> "We should expect that the outer Solar System has many more comets on these shrunken orbits compared to those on larger orbits" **Nathan Kaib**

they are no longer visible to our telescopes. "Fading among distant comets was discovered by combining the results of computer simulations of comet production with the current catalogue of known distant comets," said Kaib. "These distant comets are faint and extremely difficult to detect, and comet-observing campaigns have taken great pains to build this catalogue over the past 20 years. Without it, this work wouldn't have been possible."

But to understand what exactly is happening would require more powerful telescopes than scientists can use today. Once those are available, Kaib and his colleagues explain, astronomers will probably find out that the outer Solar System is full of faded comets. Astronomers know of comets that orbit between Jupiter and Saturn and regularly burst into powerful eruptions in spite of the cold environment, so it's clear that they can lose their matter even far away from the Sun.

COSMIC SNOWBALLS

Take a close-up look into what makes a comet

1 Nucleus

Spanning up to tens of kilometres in diameter, a comet nucleus is made up of frozen water, gases such as carbon dioxide and methane, organic molecules and dust.

2 Coma

As a comet approaches the Sun its surface sublimates, reducing frozen material into a glowing trail of gas called a coma.

3 Dust tail

A red dust tail is formed when solar radiation pressure moves dust particles into a curved tail following the comet.

4 Plasma tail

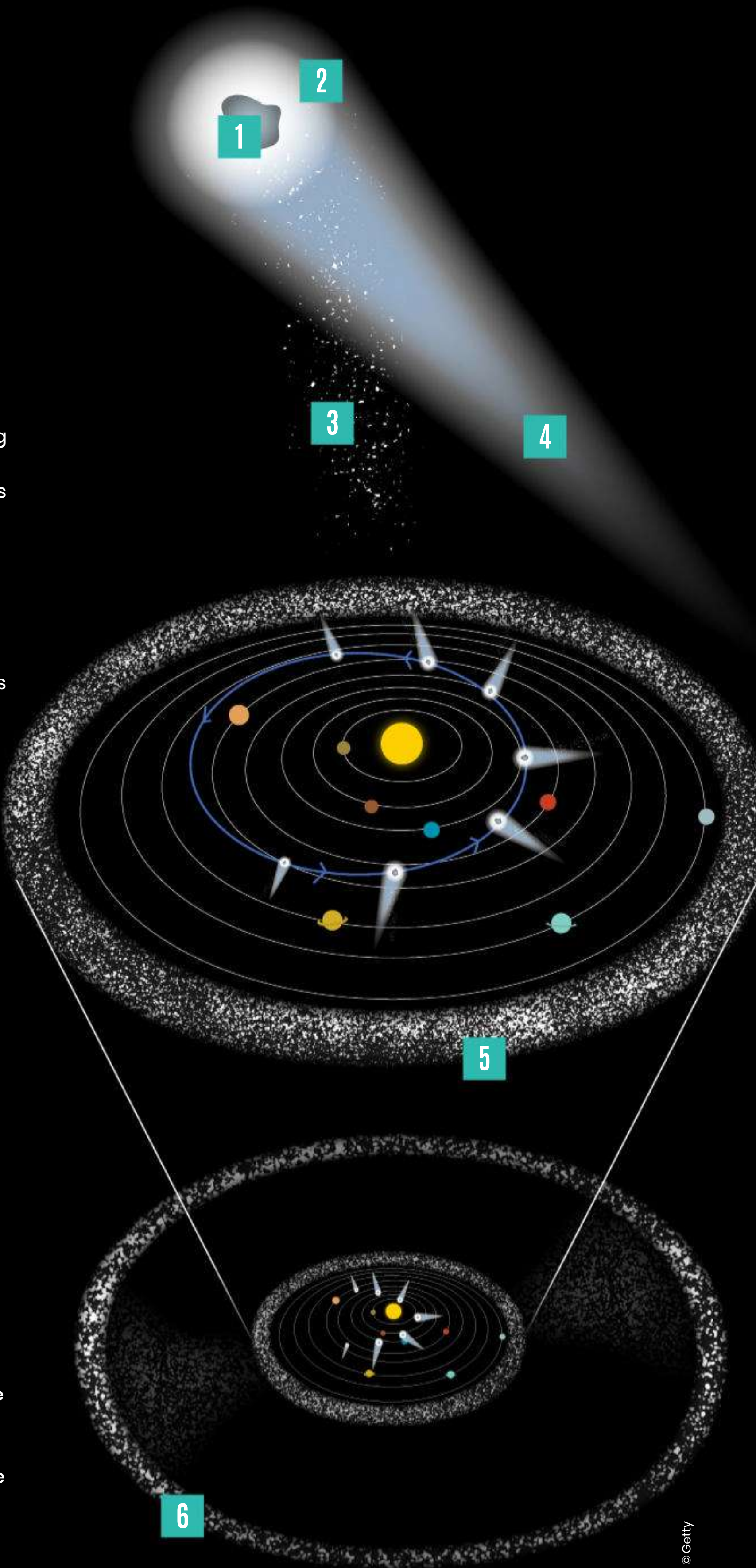
The solar wind interacts with the gaseous coma, ionising particles and pushing them away from the nucleus to create a plasma tail.

5 Kuiper Belt

A doughnut-shaped region of space just beyond Neptune that's filled with millions of icy bodies lying 4.5 to 7.5 billion kilometres (2.7 to 4.6 billion miles) from the Sun.

6 Oort Cloud

Surrounding the entire Solar System is a spherical cloud of icy debris as large as mountains. It's thought to be home to many comets.



SECRETS OF THE ICE GIANTS

AT THE FAR REACHES OF THE SOLAR SYSTEM, TWO WORLDS REMAIN A MYSTERY TO US. BUT RECENT RESEARCH MAY HAVE GIVEN US A PEEK INTO THE UNKNOWN

Written by Kulvinder Singh Chadha

Uranus and Neptune could be stranger than we once thought. On the surface these two planets – roughly midway in size between Earth and Jupiter – seem unassuming, if different from one another. Uranus is a featureless, pale-azure planet, and Neptune a deep-blue one with white cloud bands and a dark storm system similar to Jupiter's Great Red Spot. But at heart they may be much more alike, as well as unlike anything we would encounter on Earth. Studies are showing that in terms of chemistry, density, temperature and pressure, the interiors of these worlds have the complexity of a Shakespearean character, and even that they may have actual diamond rain.

Although NASA's pioneering Voyager 2 spacecraft visited both planets in 1986 and 1989, sending back a wealth of images and data, no spacecraft has been to either world since. That may be due to the fact that Uranus and Neptune are the last two official planets, lying at the planetary edges of our Solar System 2.9 and 4.5 billion kilometres (1.8 and 2.8 billion miles) from the Sun respectively. Much of our information – and all of our up-close images of these worlds – come from Voyager 2, although both are studied by ground and space-based telescopes.

The giant planets formed in the outer Solar System where hydrogen and helium were more abundant. Clearly Uranus and Neptune aren't small and rocky like the planets of the inner Solar System. But nor do they quite reach the status of 'gas giant' like Jupiter and Saturn, even though they have similar bulk compositions of hydrogen and helium by percentage. They belong to a class of their own: so-called 'ice giants'. The 'ice' refers to some of the volatile chemicals found – mostly – deep within.

One scientist, Professor Jonathan Fortney of the University of California, Santa Cruz, says: "Uranus and Neptune are generally thought of as 'failed' versions of Jupiter and Saturn. They did not accrete tens to hundreds of Earth masses of hydrogen and helium, probably because there was less gas farther from the Sun by the time they formed." Fortney is a member of the science team for a proposed future mission to the ice giants led by NASA's Jet Propulsion Laboratory, Goddard Space Flight Center and the European Space Agency.

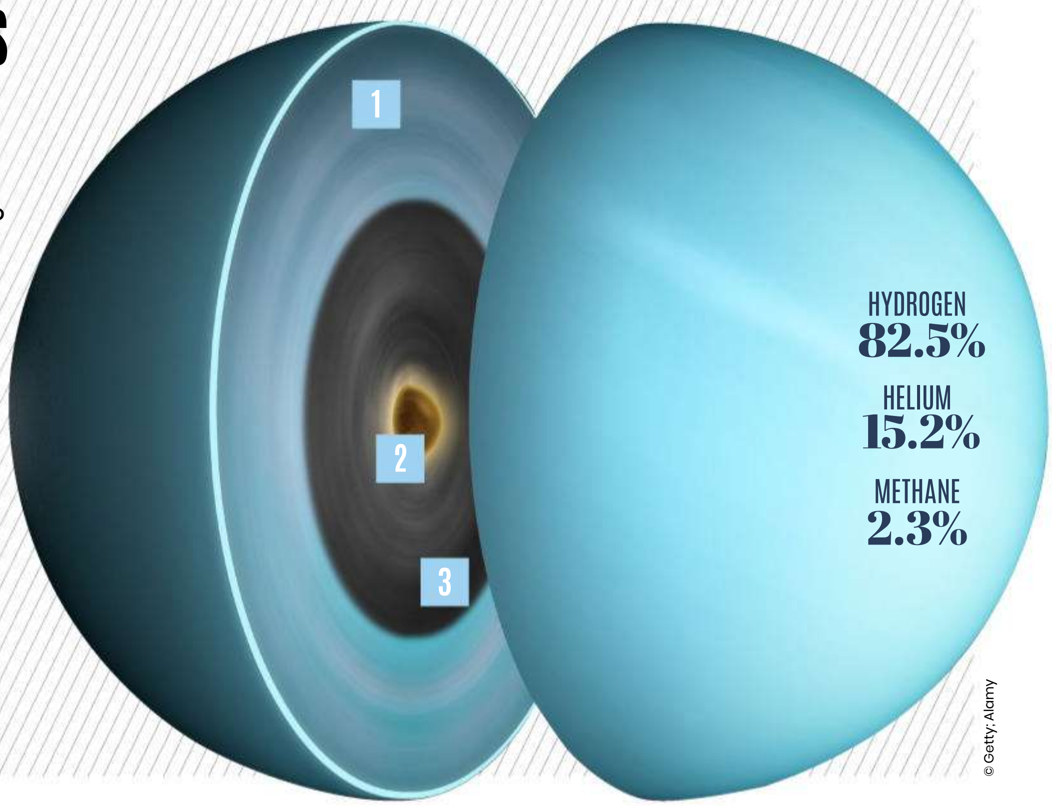
> "Uranus and Neptune are generally thought of as 'failed' versions of Jupiter and Saturn"
> **Jonathan Fortney**

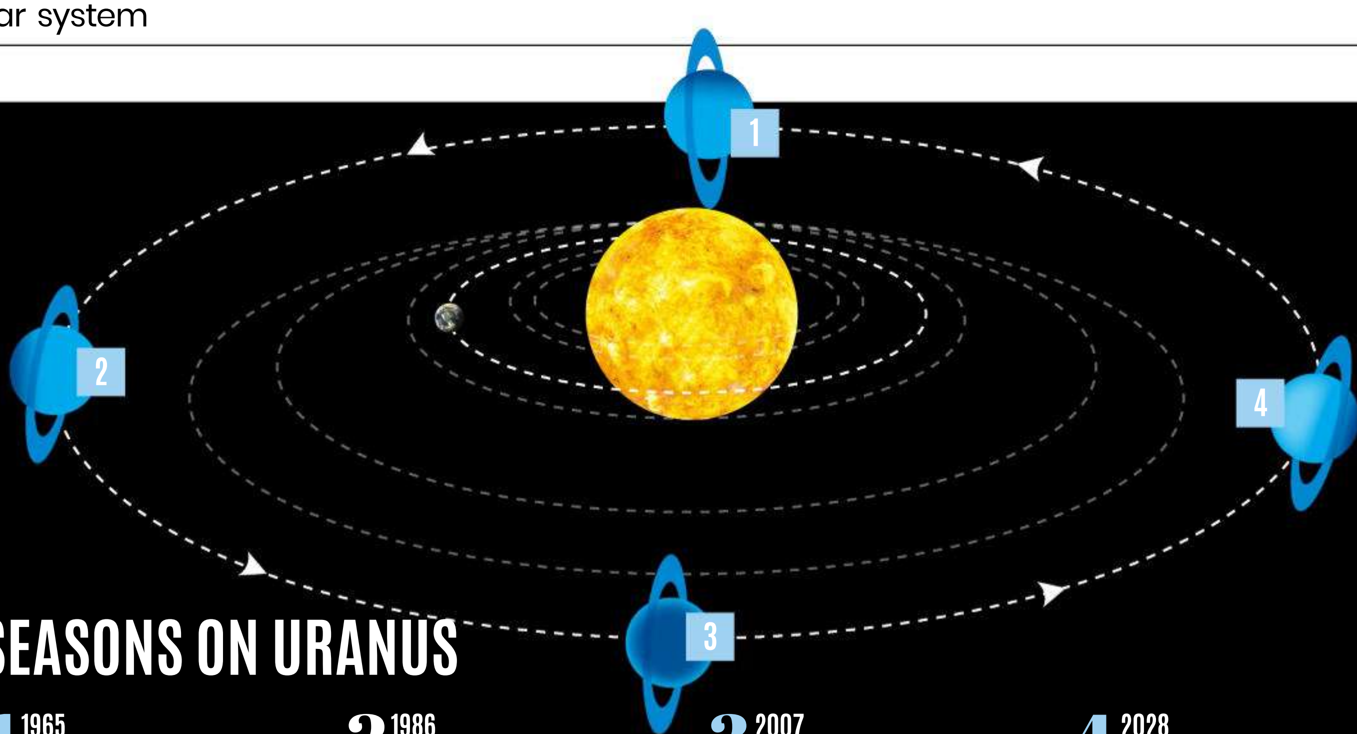
INSIDE URANUS

1 Hydrogen-helium atmosphere
Although by percentage the atmospheric composition of hydrogen and helium is similar to the other giant planets, by mass it's very low.

2 Silicate iron-nickel core
The core is thought to be a rocky, iron-nickel body 0.5 to 3.7 times Earth's mass. The precise figure is currently unknown due to the difficulty of calculating it.

3 Fluid icy mantle
Made of ammonia, water and methane ices, the mantle is the bulk of Uranus' mass, increasing in temperature and pressure towards the core.





SEASONS ON URANUS

1 1965
In this year the northern hemisphere of the planet underwent its autumn equinox while the southern half was in spring. During this time there were roughly equal measures of day and night for 21 years.

2 1986
It was back in 1986 that the Voyager 2 spacecraft flew past the ice giant during the northern hemisphere's winter, which means that the northern hemisphere was plummeted into 21 years of darkness.

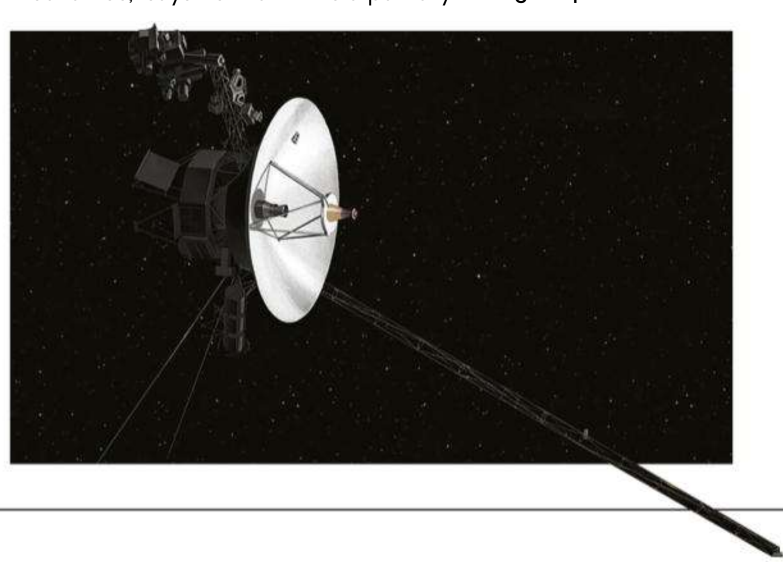
3 2007
With the rings edge-on to the Sun, the northern hemisphere's spring equinox took place around seven years ago. It's this time of year where there are 21 years of normal days and nights.

4 2028
It's winter in the southern hemisphere, while the northern hemisphere is treated to the summer solstice. As a result, the northern hemisphere receives 21 years of daytime.

Hydrogen and helium would also have evaporated close to the Sun once it started shining. This volatility also applies to the ices, which include ammonia, water and methane compounds. Water might seem like a surprising addition, but it's liquid on Earth because of the pressure of our atmosphere, if you discount temperature variations.

The current broad consensus by planetary scientists is that both planets have rocky, iron-nickel Mars to Earth-sized cores; fluid, icy mantles that are 10 to 15 times Earth's mass – with Uranus' calculated to be 13.4 times – and hydrogen-helium atmospheres with small amounts of methane. But even with the Voyager 2 data, scientists still don't really know what these worlds are like inside. Work done over the years almost always has to rely on computer simulations because the planets' internal conditions are so difficult to recreate with current laboratory equipment. Ices comprise the bulk mass of the ice giants' mantles, and their temperatures and pressures change at different altitudes. This is where the term 'ices' becomes weird in the conventional sense, because the ammonia, water and methane mixtures can reach thousands of degrees Celsius in temperature the further you go down. The reason they are able to maintain their composition is because of the soul-crushing pressures of hundreds of thousands to even millions of Earth atmospheres.

A recent study has investigated this further. An international team led by Dr Andreas Hermann of the University of Edinburgh's School of Physics and Astronomy and Centre for Science at Extreme Conditions simulated water and ammonia mixtures at low temperature conditions. The team discovered that the mixture allowed a compound called ammonia hemihydrate to remain stable as it went through ionic phases at increasingly high pressures. "There's an interesting state of matter – called superionic – where, due to heat, protons become diffuse, while the heavy atoms of carbon, nitrogen and oxygen remain in a fixed lattice," says Hermann. "It's a partially



Voyager 2 is the only spacecraft to have visited the ice giant planets

HOW AN ICE GIANT IS MADE

The ice giants formed around the Sun like their Solar System siblings

1 Cloud of gas and dust collapses

An interstellar cloud of gas and dust, known as a solar nebula, collapsed in on itself and began to spin. Our newborn Sun began to shine in the centre of this spinning disc as the temperatures and pressures triggered thermonuclear fusion.

2 Material comes together

Heavier materials in the spinning disc of gas and dust started to form into clumps. Closer to the Sun these materials included rock and iron, but beyond the frost line, which lies between the orbits of Mars and Jupiter, there were solid 'ices' like water, methane and ammonia.

3 Clumps collide and merge

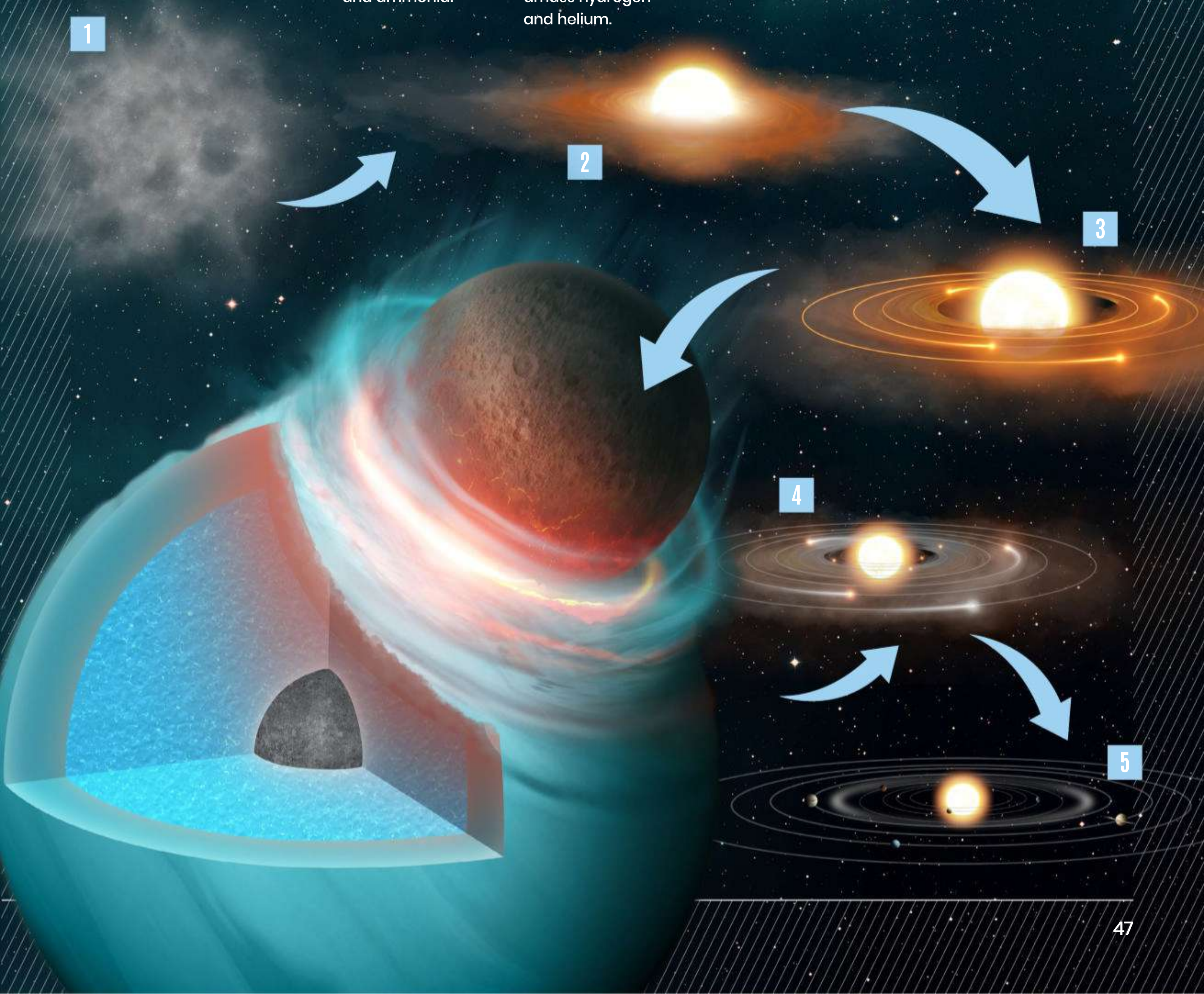
Clumps combined through collisions and started to become the building blocks of planets. Over millions of years these planetesimals increased in size through more collisions. The four giant planets beyond the frost line grew big enough to amass hydrogen and helium.

4 The planets take shape

Solar wind from the Sun dispersed any remaining gas from the Solar System, and planet formation was almost done. Uranus and Neptune are thought to have formed after the dust was swept away from the inner Solar System to its outer regions.

5 Planets get in formation

Uranus and Neptune might have formed farther in between Jupiter and Saturn and later migrated out to their final positions today over hundreds of millions of years. Uranus was likely hit by an impactor when its moons and rings were still forming.

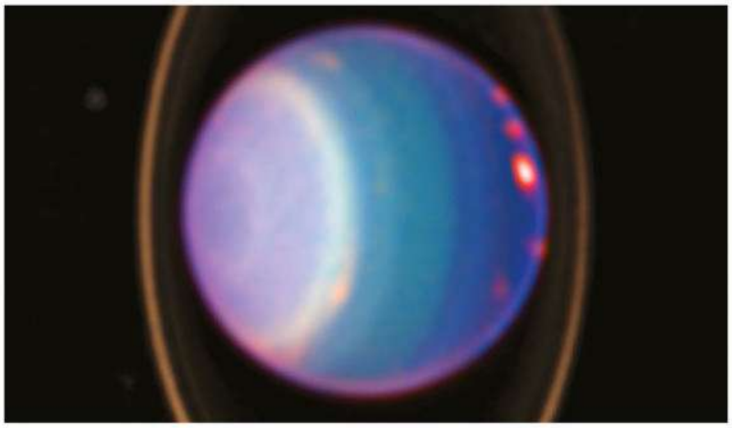


molten state that still carries signatures from the underlying crystal structures."

What this means is that molecules of superionic matter start off as a 'sea' of free-floating ions of their original selves, but then, under increasing pressure, they crystallise to become a strange liquid-solid hybrid. No superionic matter has ever actually been observed, but it's thought to exist inside giant planets. In their research paper the team say that ammonia hemihydrate will likely precipitate out of ammonia-water mixtures at high enough pressures. The reason this study is particularly important is because this result emerged from modelling a mixture of ices, instead of individual compounds, which has been the case for studies in the past.

But what else did the team's study show? "We calculated that ammonia hemihydrate has a lower density than pure water ice at the same pressure. It would then form a well-defined layer above an icy sea," explains Hermann. Imagine a solid-liquid ammonia layer above a slushy, frozen ocean at 3 million Earth atmospheres. However, he also says that truly understanding what layers would actually form, if any, would also require adding methane and excess hydrogen to the simulations. In the meantime, the team is working on simulations of superionic ammonia hemihydrate.

Though physically recreating the interiors of the ice giants may be challenging, it's not completely impossible, as has been discovered. An international team led by Dr Dominik Kraus of the University of Rostock and Helmholtz-Zentrum Dresden-Rossendorf fired a powerful X-ray laser at



This false-colour image by Hubble shows bright clouds in Neptune's atmosphere in orange

An infrared image of Uranus taken by the Keck II telescope shows storm-like features and clouds

HOW THE ICE GIANTS' WEATHER SYSTEMS COMPARE WITH OTHER WORLDS

The climate is very different across distant worlds

EARTH

Type of rain: Water
Average temperature: 16 degrees Celsius (61 degrees Fahrenheit)
Day: 24 hours
Year: 365 days

VENUS

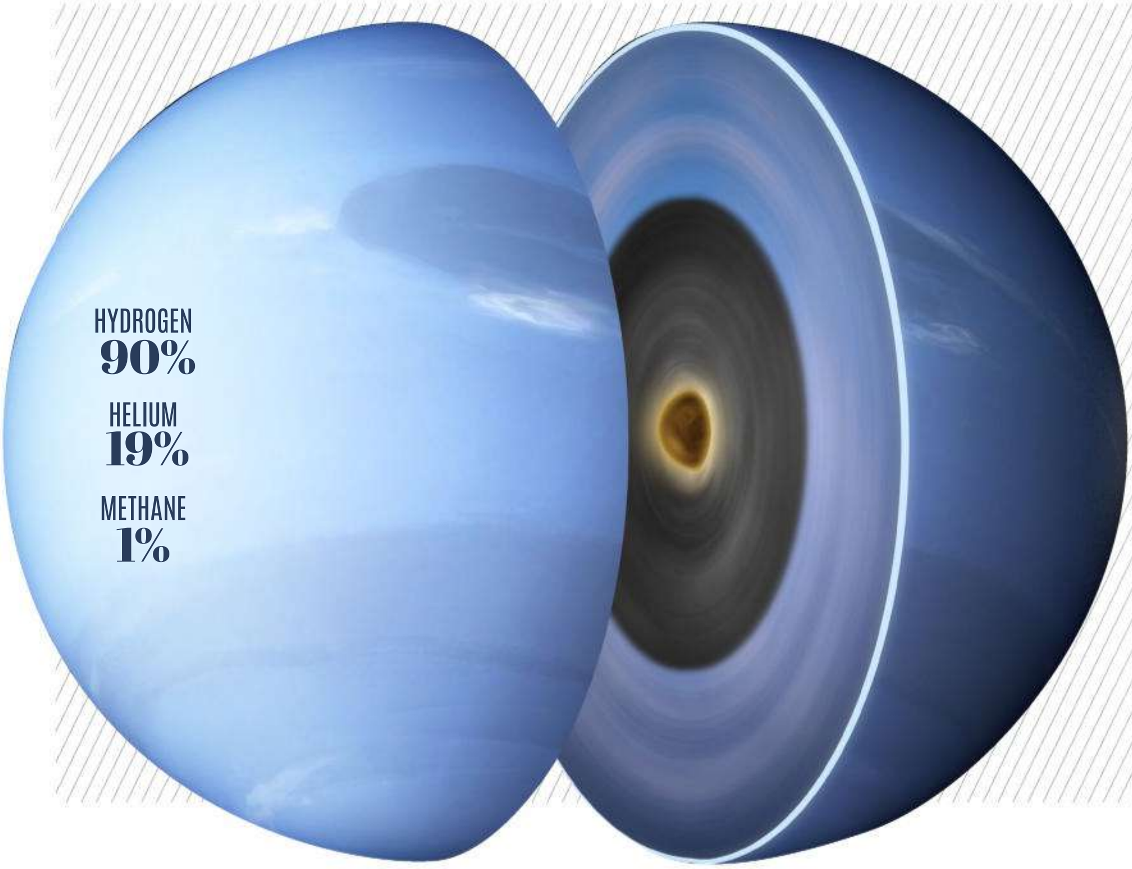
Type of rain: Sulphuric acid
Average temperature: 462 degrees Celsius (864 degrees Fahrenheit)
Day: 116 days
Year: 225 days

HD 189733 B

Type of rain: Glass
Average temperature: 843 degrees Celsius (1,549 degrees Fahrenheit)
Day: 13 days
Year: 2.2 days

URANUS

Type of rain: Diamond
Average temperature: -216 degrees Celsius (-357 degrees Fahrenheit)
Day: 17 hours
Year: 84.3 years



INSIDE NEPTUNE

1 Hydrogen-helium atmosphere

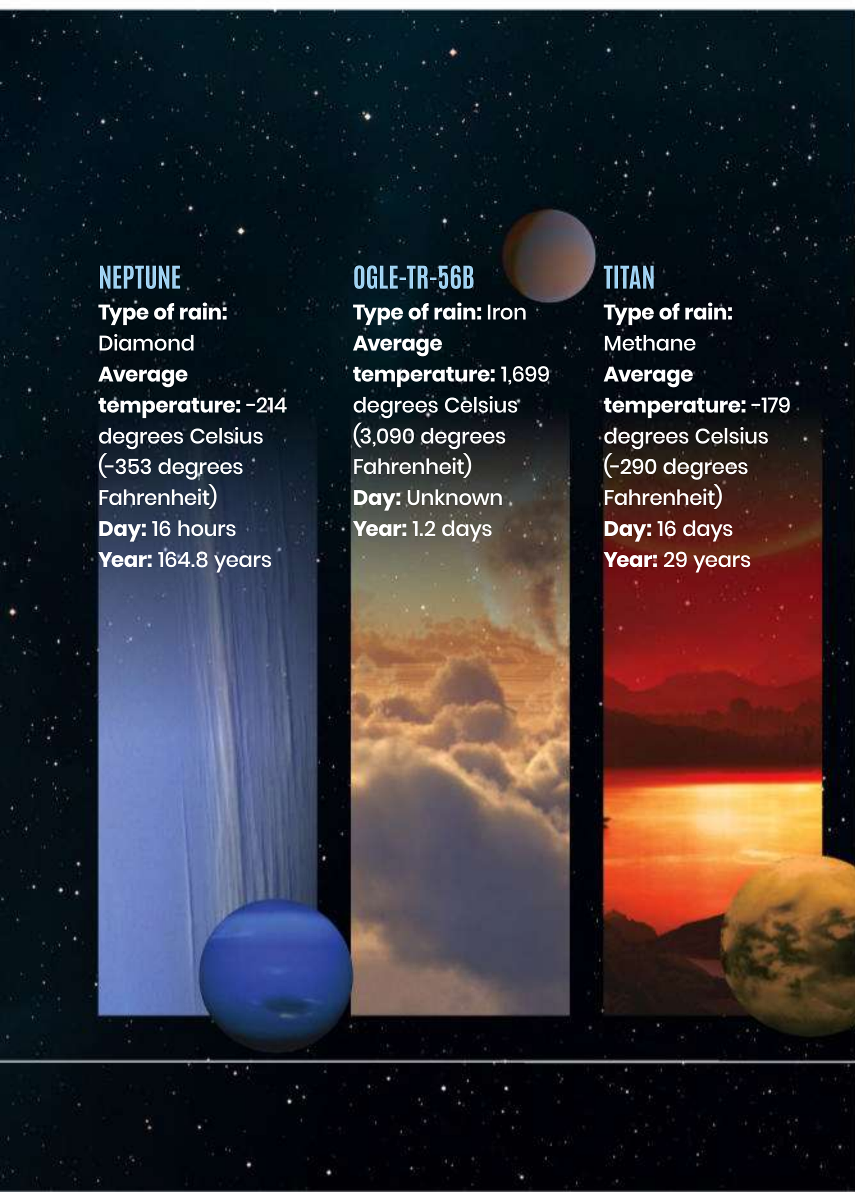
It has a hydrogen-helium atmosphere, albeit with a more dynamic climate and prominent upper clouds. The nature of the deep-blue colour is unknown.

2 Silicate iron-nickel core

Neptune has a rocky iron-nickel core that's at least as massive as Earth. Pressures at its centre could reach 7 million Earth atmospheres.

3 Fluid icy mantle

Neptune's bulk mass is composed of a mantle made of ammonia, water, methane and other ices. Recent experiments suggest a carbon ocean.

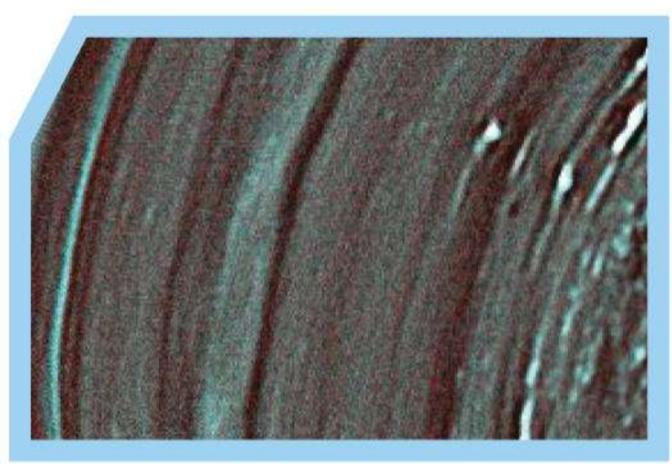


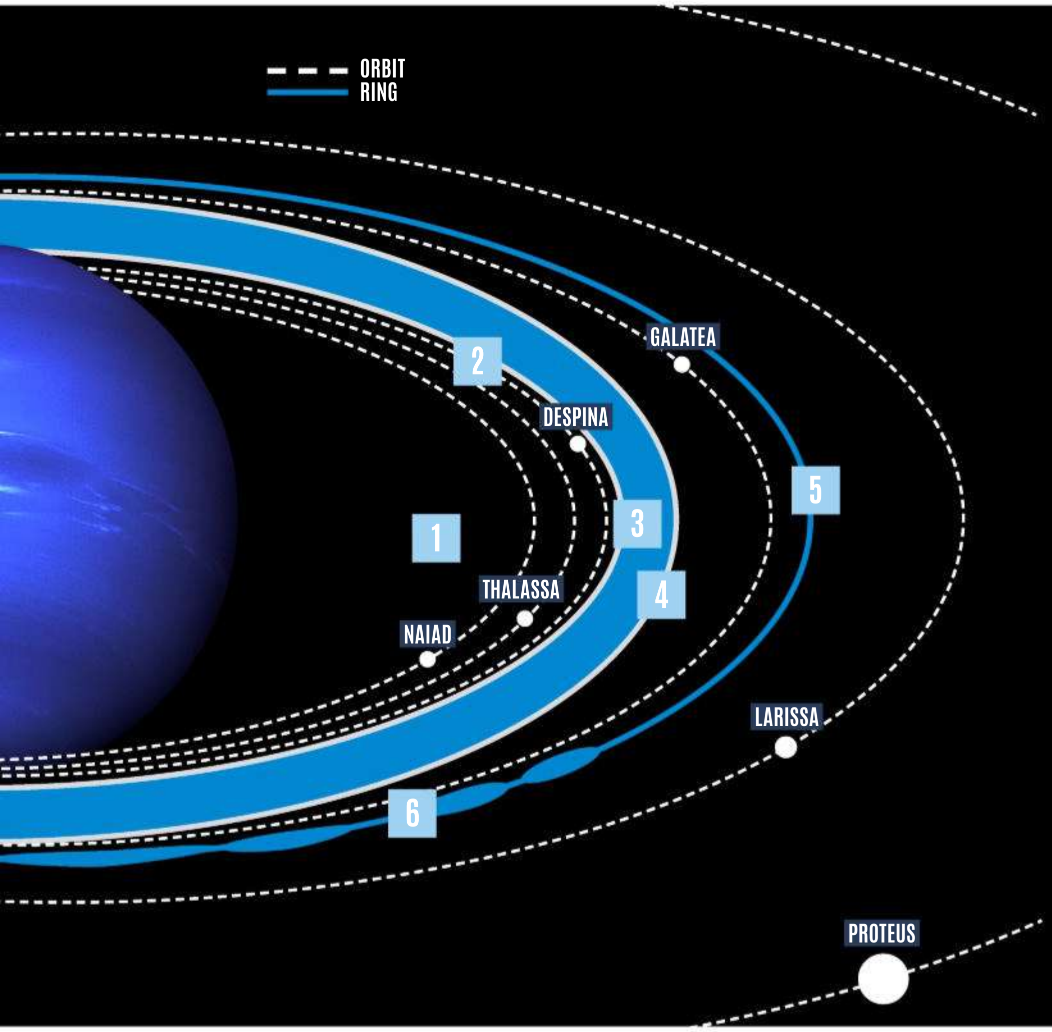
NEPTUNE
Type of rain: Diamond
Average temperature: -214 degrees Celsius (-353 degrees Fahrenheit)
Day: 16 hours
Year: 164.8 years

OGLE-TR-56B
Type of rain: Iron
Average temperature: 1,699 degrees Celsius (3,090 degrees Fahrenheit)
Day: Unknown
Year: 1.2 days

TITAN
Type of rain: Methane
Average temperature: -179 degrees Celsius (-290 degrees Fahrenheit)
Day: 16 days
Year: 29 years

pieces of polystyrene at the SLAC National Accelerator Laboratory. The polystyrene was meant to be a stand-in for methane inside ice-giant mantles – both made of carbon and hydrogen – and the laser created two shock waves within it. Under those conditions, the shock waves overlapped, creating pressures of 1.5 million atmospheres and temperatures of 5,000 degrees Kelvin for fractions of a second – briefly mimicking the conditions inside an ice-giant mantle. The team was surprised to discover that diamond was created, albeit nanometres in size. They theorise that in the more sustained conditions of an ice-giant mantle – around 10,000 kilometres (6,214 miles) down – the diamonds will grow to a larger size as the methane breaks down into hydrogen and carbon and precipitate down to the core. Previous teams have used methane inside laboratory diamond anvil cells to create





THE RINGS OF NEPTUNE

1 Galle
Galle is 2,000 kilometres (1,240 miles) wide; it orbits Neptune at 41,000 to 43,000 kilometres (25,500 to 26,700 miles).

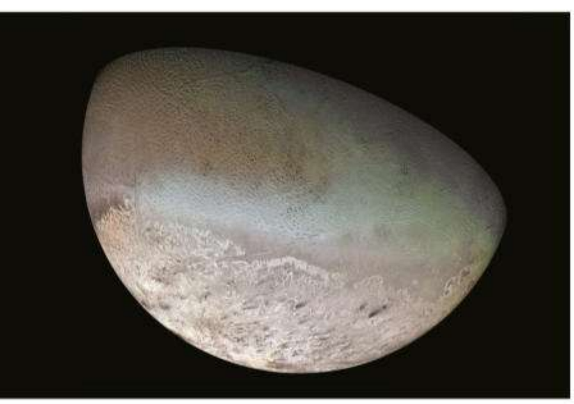
2 Le Verrier
113 kilometres (70 miles) wide, it orbits 53,200 kilometres (33,000 miles) away.

3 Lassell
Lassell is more like a broad dust sheet than a ring, with its orbit around Neptune between 53,200 and 57,200 kilometres (33,000 and 35,500 miles).

4 Arago
Arago orbits Neptune at 57,200 kilometres (35,500 miles) and is less than 100 kilometres (62 miles) wide.

5 Adams
Adams is 35 kilometres (22 miles) wide and orbits around Neptune at 62,900 kilometres (39,000 miles).

6 Arcs
These arcs are the particles of dust clustered together in the Adams ring, named Fraternité, Égalité 1, Égalité 2, Liberté and Courage.



Moons such as Neptune's Triton will be studied by future missions

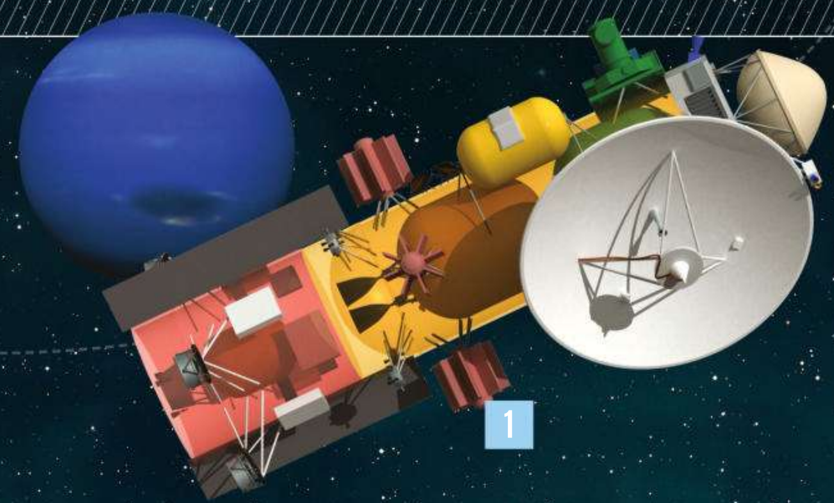
diamond, but under lower temperatures and pressures. However, the results were always inconclusive.

In another study, Lawrence Livermore National Laboratory scientists subjected a diamond to 1.1 million Kelvin and 40 million atmospheres to recreate the conditions inside giant planets. Results suggested that at the bottom of the ice giants' mantles could lie a liquid-carbon layer with chunks of floating diamond.

Kraus' team are now working on follow-up experiments. "Our efforts have now turned to looking at what happens when we reduce the carbon concentration in our samples and add other light elements that are also present inside Neptune and Uranus, such as oxygen or nitrogen," he explains. They're also figuring out ways to safely capture the nanodiamond particles, which travel at incredibly high speeds and are currently only detected via spectroscopy.

The work done so far may help solve another mystery: why Uranus radiates less excess heat than it receives from the Sun compared to all the other giant planets. Even Neptune, which is farther from the Sun, radiates 2.6 times as much heat as it receives. This heat energy may be what drives Neptune's storm systems and gives it a more dynamic climate than Uranus. It's been suggested that somewhere inside Uranus is a thermal boundary layer that stops heat from escaping. Hermann says that if the planet's layers are more stratified than thought, "it's not inconceivable that ammonia hemihydrate, or similar strongly bound ionic phases, could form such a layer." Such work could ultimately help in understanding not only the ice giants, but all the giant planets. As Fortney says: "The deep cores of Jupiter and Saturn may actually resemble Uranus and Neptune, but at much higher pressures and temperatures."

Kulvinder Singh Chadha
Space science writer
Kulvinder is a freelance science writer, outreach worker and former assistant editor of *Astronomy Now*. He holds a degree in astrophysics.



MISSIONS TO URANUS AND NEPTUNE

NASA reports suggest several possible future spacecraft to the ice giants

Neptune orbiter with probe

Launch date: 2030s
Mission length: 15 years

1 A minimum 50-kilogram science payload would be required for a mission to Neptune. This would include both the orbiter and probe's science packages. The orbiter would study Neptune's moons – particularly Triton, which is a captured Kuiper Belt object. It would also study Neptune's weather systems, magnetosphere and solar wind particles at this distance. The atmospheric probe would be required to accurately measure the abundance of noble gases, including hydrogen and helium, and other elements.

Uranus orbiter only

Launch date: 2030s
Mission length: 15 years

2 This would weigh three times as much as the other concepts, but carry five times as many instruments. Alongside a narrow-angle camera and instruments for measuring magnetic fields and interior atmospheric structure, the orbiter will have spectrometers, a dust detector and other devices. It would have a wide-angle camera for snapping wide vistas of the planet, its moons and rings. It may clear up long-standing mysteries. One big mystery of Uranus is why it radiates so little heat compared to the other giant planets.

Uranus orbiter with probe

Launch date: 2030s
Mission length: 15 years

3 An orbiter and probe would have a major advantage over a flyby. While the probe studied the planet's atmospheric layers, the orbiter could study the moons and ring system in great detail. As a comparison to Cassini, unexpected discoveries such as plumes of water ice on Enceladus were a fortunate consequence. A Uranus orbiter-probe would be almost the same as the Neptune orbiter-probe concept. It's thought both planets' moons harbour water in some form. This would be of value in understanding both planets' environments.

Uranus flyby with probe

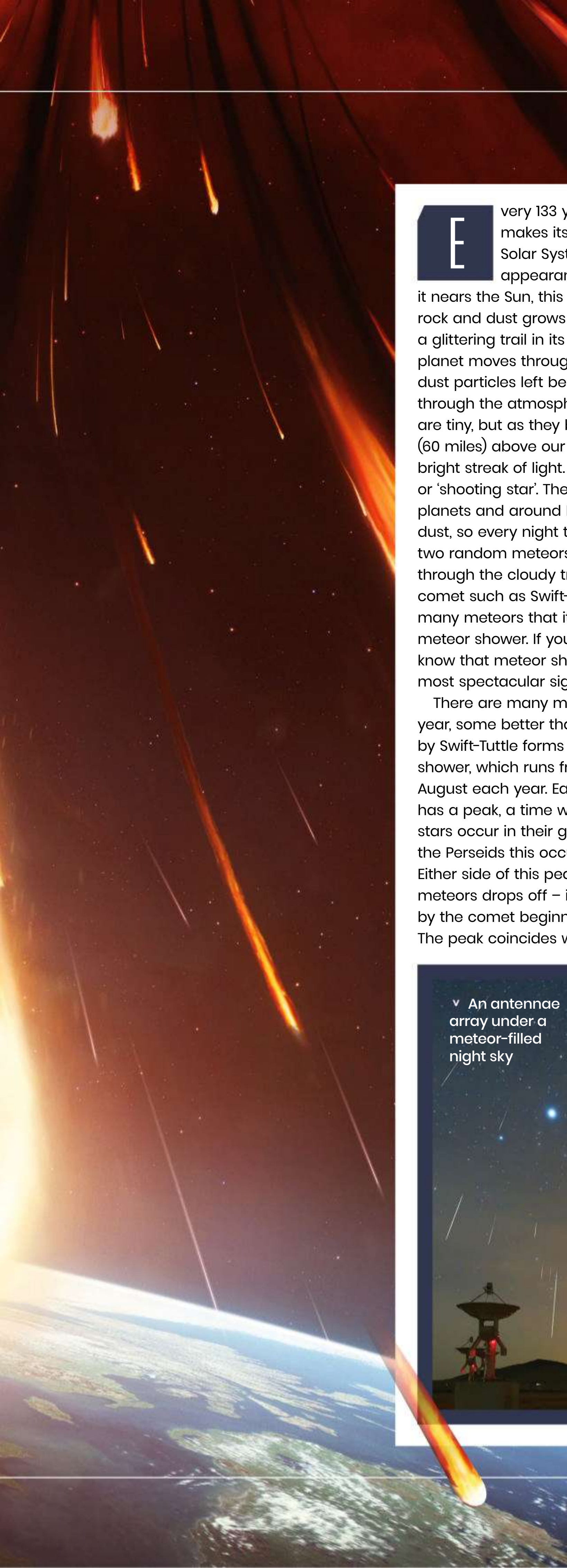
Launch date: 2030s
Mission length: 10 years

4 A flyby, weight for weight, would be the cheapest ice-giant mission option, and it would achieve many of the same science objectives. However, a flyby mission wouldn't have much time to study the planet, its moons or ring system. It would have to work fast and release its probe. As with Neptune, the probe would be required to measure the abundance of hydrogen, helium, heavier noble gases and other elements such as volatiles in the atmosphere. Although not the same as Neptune, a lot could be inferred from it by studying Uranus.

COMETS, ASTEROIDS & METEOR SHOWERS

Racing through space and crashing into Earth's atmosphere, All About Space discovers the space rocks that litter our Solar System

Reported by Colin Stuart



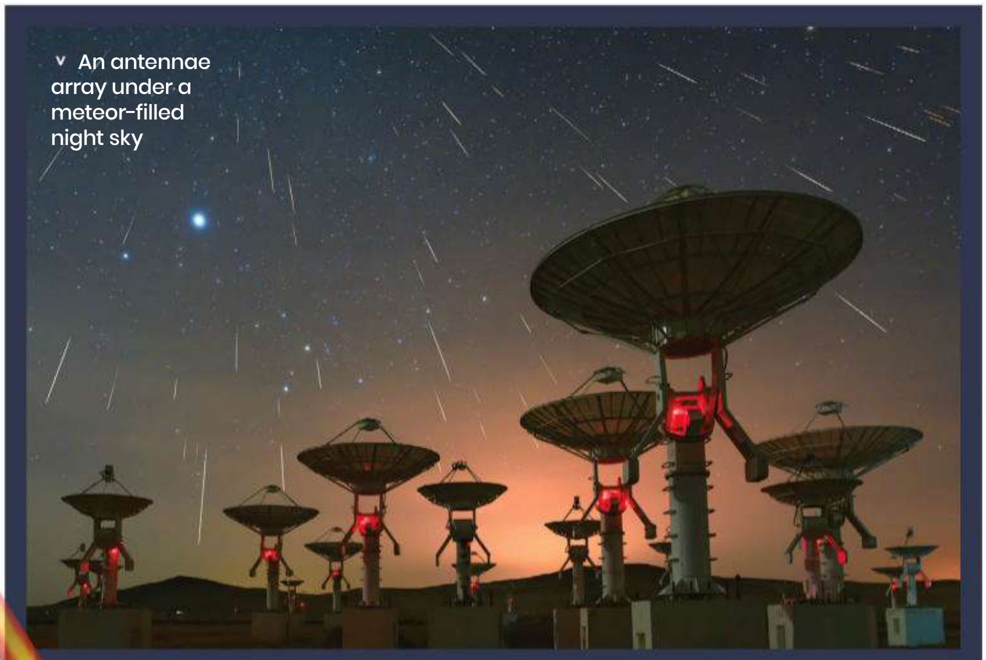
Every 133 years, Comet Swift-Tuttle makes its return to the inner Solar System. It last made an appearance in 1992. Each time it nears the Sun, this speeding ball of ice, rock and dust grows a tail that deposits a glittering trail in its wake. Every year our planet moves through this, causing the dust particles left behind to come crashing through the atmosphere. Most of them are tiny, but as they burn up 100 kilometres (60 miles) above our heads they leave a bright streak of light. We call this a meteor, or 'shooting star'. The space between the planets and around Earth's orbit is full of dust, so every night there will be one or two random meteors. When Earth travels through the cloudy trail of dust left by a comet such as Swift-Tuttle, there are so many meteors that it's described as a meteor shower. If you've seen one, you'll know that meteor showers are among the most spectacular sights in the night sky.

There are many meteor showers each year, some better than others. The dust left by Swift-Tuttle forms the Perseid meteor shower, which runs from 17 July to 24 August each year. Each meteor shower has a peak, a time when the shooting stars occur in their greatest number. For the Perseids this occurs on 12 August. Either side of this peak, the number of meteors drops off – imagine the trail left by the comet beginning to spread out. The peak coincides with the densest part of the trail, and the most active meteor showers can produce more than 100 shooting stars per hour.

Other great meteor showers include the Quadrantids in January, which peak on the 3rd; the Lyrids between 16 and 25 April; the Orionids that peak on 21 October; the Leonids that are at their maximum on 17 November and the Geminids, which are at their best on 14 December. The names of the meteor showers come from the constellations in which they appear to streak from – this is the direction in which Earth is moving through the dust trails. For example, the Perseids streak across the sky from their 'radiant' in Perseus, the Leonids from Leo and the Geminids from Gemini.

The Geminids are unique among meteor showers. All the rest are produced by dust from comets, but the Geminids are produced by dust left by an asteroid, 3200 Phaethon. This goes to show that sometimes the lines between asteroids and comets can be blurred. Astronomers have even witnessed some asteroids in the asteroid belt acting like comets by growing a tail.

"If you've seen one, you'll know that meteor showers are among the most spectacular sights in the night sky"

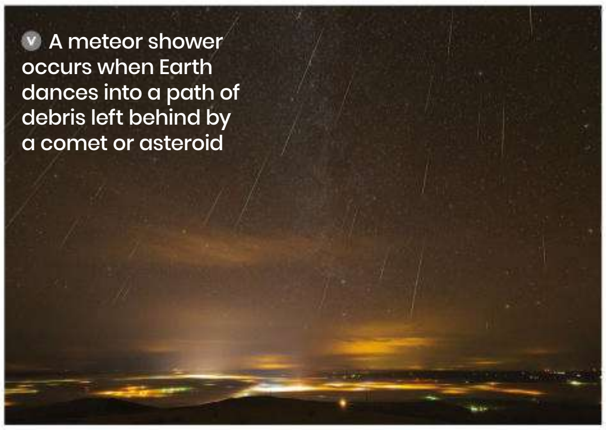


An antennae array under a meteor-filled night sky

Counting meteors is scientifically important. Differences in the speed, direction, brightness and colour of meteors can tell us a lot about the nature of the object that produced them. For example, Geminid meteors tend to move more slowly than meteors left by comets, and they burn up at a much lower altitude, about 38 kilometres (24 miles) above ground.

Occasionally, a meteor entering the atmosphere is a little larger than the rest. Rather than just leaving the thin streak of a shooting star, they are bigger and brighter, sometimes even brighter than Venus. These are fireballs that are burning up lower in the atmosphere. The brightest are called bolides – if you're lucky enough to see one, you might even see flaming chunks breaking off. Meteors around 20 to 30 metres (66 to 98 feet) in size will explosively fragment in the atmosphere, causing an airburst like the dramatic event that occurred over the Russian city of Chelyabinsk in 2013. This exploded 30 kilometres (18 miles) above the ground, and the shock wave shattered windows, damaged roofs and sent 1,500 people to hospital with cuts from flying glass.

The biggest meteors can actually reach the ground before they completely disintegrate. We call these meteorites, and over 60,000 of these have been found on Earth. Most are chunks of rock smaller than your hand, and the most common place to find them is in the white, icy landscape of Antarctica or a barren desert. Here the charred, black rocks stand out like a sore thumb. Not all meteorites come from asteroids – a handful come from the Moon and Mars.



A meteor shower occurs when Earth dances into a path of debris left behind by a comet or asteroid

NASA and the Japan Aerospace Exploration Agency (JAXA) have both launched asteroid sample-return missions, where a craft visits a celestial body and brings back material for examination on Earth. But meteorites are naturally occurring samples, bringing pieces of other celestial bodies to Earth. They're not pristine, having been blasted into space – probably as the result of an impact – before being burned in the atmosphere and landing on the ground on Earth. But they can tell us a great deal about the geology and chemistry of planets and asteroids. There has been speculation that some of the 277 meteorites from Mars contain evidence for life in the form of microbial fossils. This was a claim made by NASA scientists in the 1990s after examining a meteorite from Mars called ALH 84001, which was found in the Allan Hills region of Antarctica in 1984. Unfortunately, most scientists are now convinced that the microscopic features are not fossils at all, or if they are then they are fossils of microbes from Earth that contaminated the meteorite while it lay on the ice in Antarctica.

Meteorites can also tell scientists plenty about the dawn of the Solar System and the birth of Earth. This is because many meteorites represent debris left over from the distant era when the planets were forming 4.5 billion years ago. They are broadly split into three types: stony meteorites, iron meteorites and a mixture of the two. Stony meteorites, especially a specific type called chondrites, make up the vast majority of meteorites and are the same type of rock that built planets like Earth. They are very primitive, having never really melted, and so they preserve the chemical building blocks of the planet-forming disc that surrounded the young Sun.

The other type of stony meteorites are called achondrites, and these have melted – either in the impacts that blasted them off their original asteroid or when they were buried deep inside a large asteroid where conditions were hot. Achondrites are special because they tell us about the chemical conditions within large asteroids and the protoplanets similar to those that eventually became the true planets.

Iron meteorites also come from the cores of protoplanets, because that's where all the iron sank to when they formed. Iron meteorites are incredibly hard and dense,

ASTEROID TYPES

The differences between four main categories of these space rocks explained

253 Mathilde

C-type Carbonaceous

They're so dark due to their carbon-black surfaces that even the largest require a telescope to detect. They consist mostly of clay and silicate rocks and account for more than 75 per cent of all asteroids. Most of these ancient space rocks orbit in the outermost regions of the asteroid belt.

433 Eros

S-type Stony

This class of asteroids orbit the inner asteroid belt and are primarily composed of stony materials, metallic nickel-iron as well as iron and magnesium silicates. S-types are the second most common asteroids and are also among the brightest – some larger examples, such as 7 Iris, can be spotted with binoculars.

21 Lutetia

M-type Metallic

M-types are pure metal, or mixtures of metal and small amounts of stone, and have originated from the cores of planetary bodies that have been broken apart by impacts. Most are metallic, comprising largely of nickel-iron, and they are found in the middle region of the asteroid belt.

4 Vesta

V-type Vestoid

V-types have similar surface properties to 4 Vesta, one of the largest asteroids in the Solar System. They're not so different in composition to S-type, also made from stony iron and chondrites, but they contain higher levels of silicon-aluminium oxides called pyroxenes. They are a reddish colour.

NAMING SPACE ROCKS

Depending on their size and what they're made of, space rocks take on new names

1 Meteor shower

These occur at the same time every year, when Earth passes through a region that has a large concentration of debris shed from either a comet or an asteroid. From our location on Earth, meteors appear to originate from the same location year after year.

2 Comet

These bodies are made of ice, rock, dust and frozen gases. Comets have a nucleus and show off a brilliant tail when they get closer to the Sun. As they disintegrate, some comets leave a trail of solid debris.

3 Meteoroid

A small rocky or metallic body that races through space, meteoroids are quite a lot smaller than their larger cousins, asteroids. Lumps of space rock that are even smaller than meteoroids are classified as micrometeoroids, or space dust.

4 Asteroid

Any large lump of space rock over one metre (3.3 feet) in size is classed as an asteroid. They often pass our planet and are found most commonly in the asteroid belt between Mars and Jupiter.

5 Meteor

The streak of light that's thrown out by a meteoroid or asteroid as it enters the atmosphere at high speed. The brightness comes as the rock rubs against air particles to make friction, heating the meteor.

6 Fireball

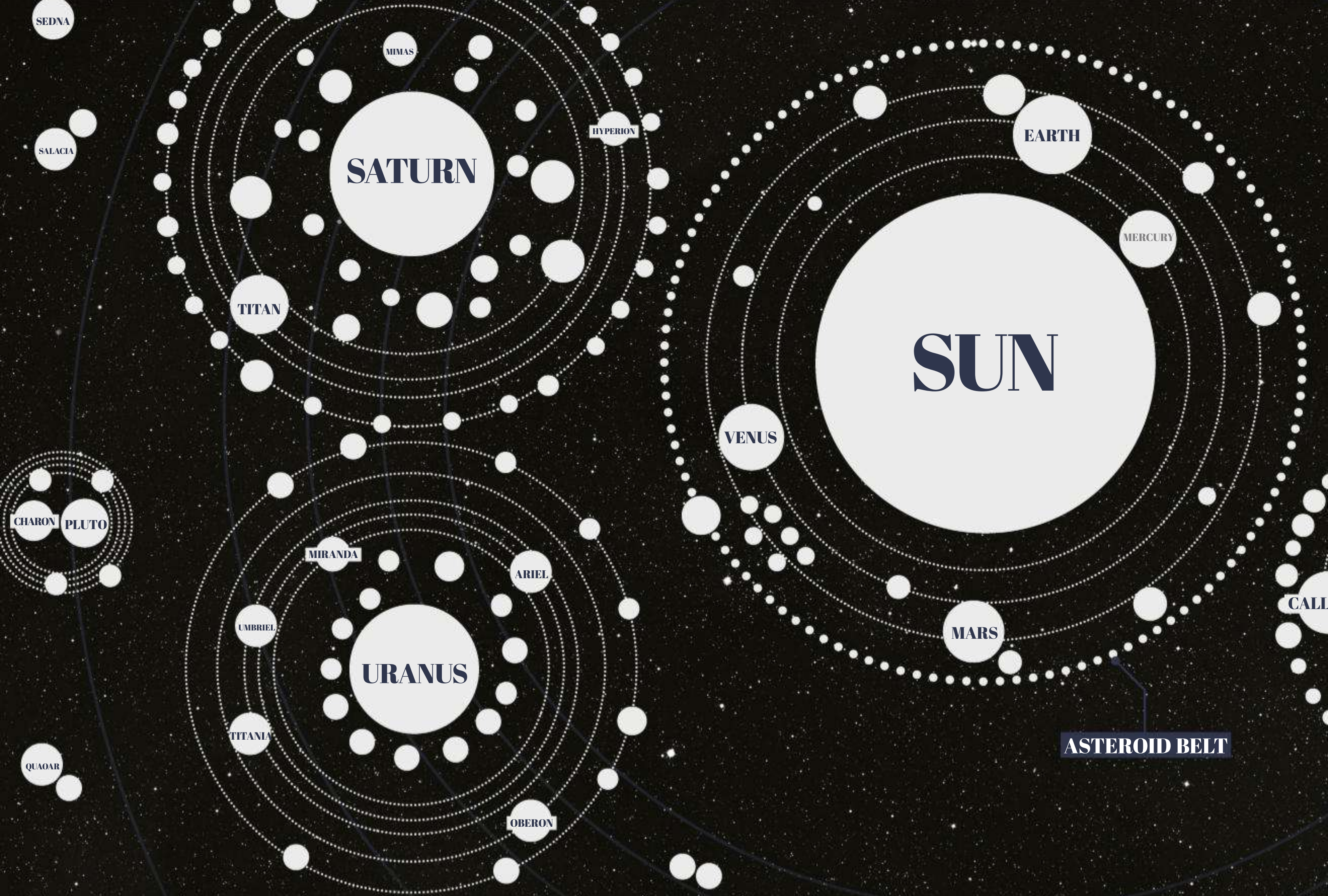
This is another term for a very bright meteor. If you ever see a fireball streaking through the night sky, you'll quickly notice its bright-white to orange hue outshines that of the brightest planet in the sky, Venus.

7 Bolide

Similar to fireballs, but in this instance their brightness is likened to that of a full Moon and even brighter. Bolides often explode in the atmosphere.

8 Meteorite

If a piece of another celestial body survives its passage through the atmosphere and touches down on the ground, we call this piece of space rock a meteorite. They can weigh in at anything from a few grams up to dozens of tonnes.



CELESTIAL BODIES

Discover some of the many dwarf planets and moons orbiting in our Solar System

Makemake

Found around 4.2 billion miles from the Sun, just outside the orbit of Neptune, this dwarf planet is the second-brightest object in the Kuiper Belt – the first being Pluto. Its discovery in 2005 prompted the International Astronomical Union to form a new classification of celestial bodies, called dwarf planets.

Haumea

Haumea sits in the Kuiper Belt and is one of the fastest rotating large objects in the Solar System. A single day on Haumea is equivalent to four hours on Earth, but due to its proximity to the Sun, one Haumean year is equal to 285 Earth years. This oval-shaped dwarf plane has two moons: Namaka and Hi'iaka.

Io

Io is one of the most volcanically active bodies in the Solar System. There are hundreds of volcanoes on the moon's surface, each of them spewing lava dozens of miles high, along with lakes of molten silicate. It's thought that Jupiter's intense gravitational pull is the reason for Io's explosive nature.

Callisto

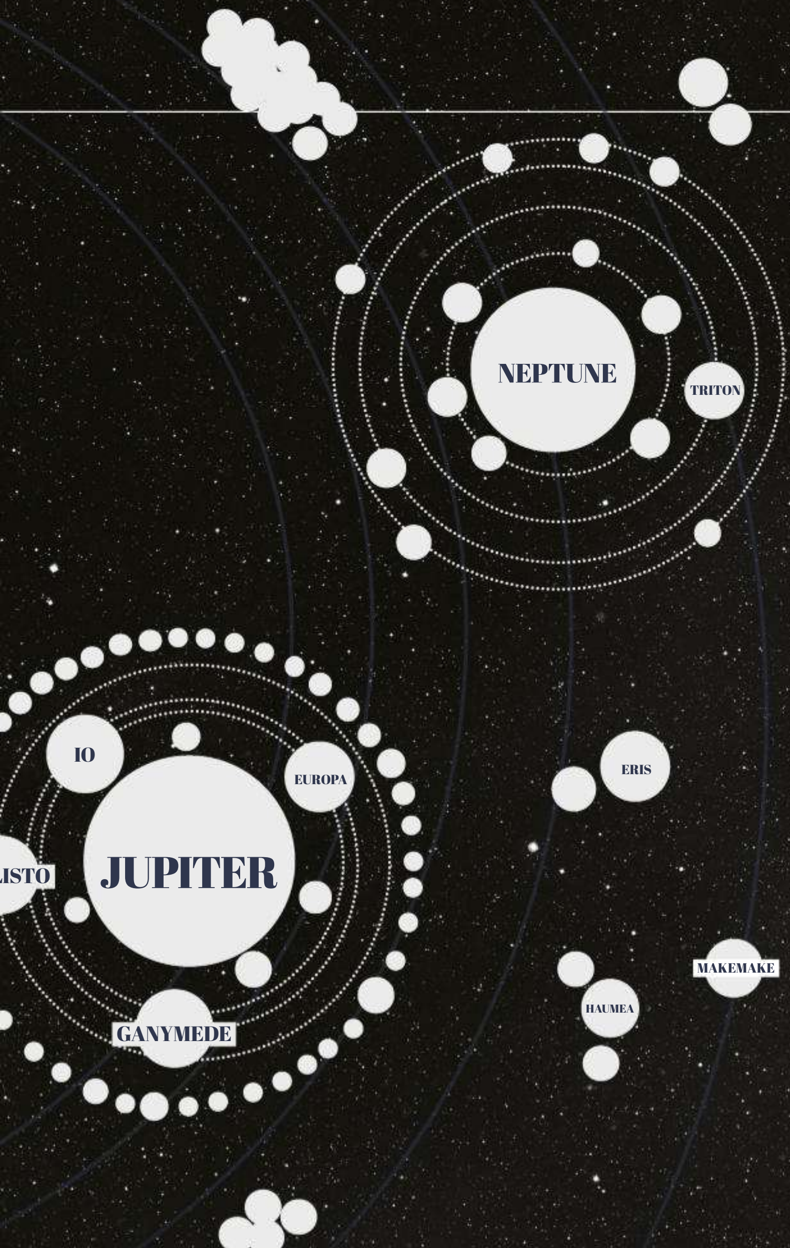
Callisto has a circumference of 9,410 miles, which is almost as big as Mercury. Not only is this moon impressively large, it has a salty secret deep below its icy surface. Discovered in 1610, it wasn't until the 1990s that scientists proposed the moon has a subsurface ocean about 155 miles below its surface.

Europa

Another of Jupiter's many moons, Europa is one of the oddest. With a surface temperature of around -160 degrees Celsius, this frozen satellite bears strange streaks. These markings are thought to be cracks in the moon's icy surface, caused by the tidal forces of an ocean deep beneath it.

Titan

Although the structure of Titan remains unclear, scientists think its core is made of rock around 2,500 miles in diameter, surrounded by water ice. This satellite has a dense atmosphere, which gives it its yellow hue. The composition of this atmosphere is primarily nitrogen and some methane.



Mimas

Often called the Death Star moon for its similarity to the space station in Star Wars, Mimas is one of Saturn's smallest moons. Its iconic impact crater, named Herschel after English astronomer William Herschel, who discovered Mimas in 1789, spans 80 miles and reaches 3.5 miles high at its peak.

Hyperion

Not all moons are spherical. Some, like Saturn's sponge-like moon Hyperion, are irregular and filled with deep caverns. With a lower density than water, this moon is made up of water ice and frozen methane or carbon dioxide. Hyperion's appearance is thought to be the result of its distance from Saturn.

but only five per cent of all meteorites are of this variety. There are two types of stony-iron meteorites: pallasites and mesosiderites. Pallasites are recognisable thanks to their large crystals of a green mineral called olivine. Mesosiderites are more of a jumble of rock and metal, made when two asteroids collide in space, with the impact fusing different materials together.

On rare occasions, a really big meteor will enter Earth's atmosphere. These are sometimes big enough to blow out large craters or explode over towns and cities, causing harm. Over 100 years before the Chelyabinsk meteorite, a similar airburst flattened 80 million trees in Tunguska, a remote region in Siberia.

These events greatly worry scientists, who fear that one day an asteroid will hit us that could destroy a city or send so much dust into the air it would block out the Sun and end life on Earth. It's a big concern to Queen founder and astrophysicist Dr Brian May, who lends his support to the Asteroid Day event to raise awareness about this threat: "30 June was the anniversary of Tunguska in 1908. Not a huge object, but it exploded before it hit the ground, which flattened the trees for hundreds of miles around. Now that is a city destroyer – the force of a thousand atom bombs."

To forewarn us, NASA's Spaceguard program has found over 90 per cent of asteroids larger than a kilometre (0.62 miles) that come close to Earth. These are the real killers, like the asteroid that wiped out the dinosaurs 65 million years ago. However, there are still millions of undiscovered asteroids out there smaller than 100 metres (328 feet) that could still do serious damage.

Astroid-surveying missions remind us that we still have much to do to protect ourselves from asteroids. Comets can also be a danger, but because there are fewer of them they pose less of a risk. Instead Earth is more likely to fly through their tails so we can see spectacular meteor showers in the sky. From shooting stars to fireballs, meteors and meteorites, their origins are all the same, just on vastly different scales.

Colin Stuart
Science author and speaker
Colin holds a degree in astrophysics, has written over 17 books on space and has an asteroid named in his honour: 15347 Colinstuart.

^ Near-Earth objects are monitored by many organisations to prevent disaster

v Meteor showers are a truly stunning sight as pieces of comet dust burn up in the atmosphere

DEEP SPACE

Go beyond the Solar System and uncover the mysteries of the universe

“Stars spend their entire lifetimes resisting gravitational collapse”

Laura Mears

50 AMAZING FACTS ABOUT BLACK HOLES

Few things are as universally awe-inspiring and terrifying as black holes. These invisible behemoths are the great architects and the great destroyers of the universe

Written by Laura Mears

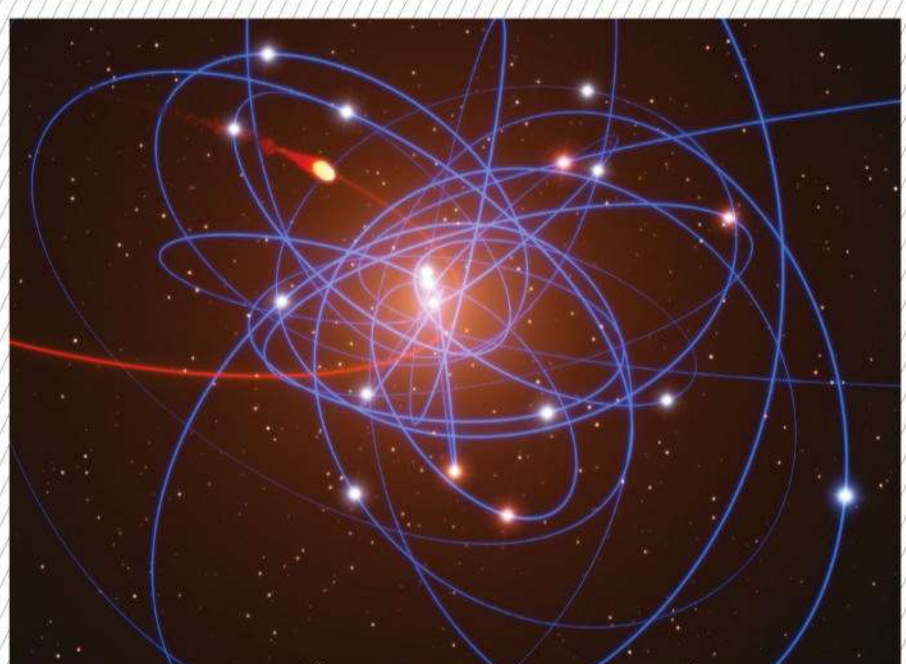
1 MANY BLACK HOLES STARTED LIFE AS STARS

Stars spend their entire lifetimes resisting gravitational collapse. Their enormous masses mean that their gas is continually pulled towards their cores, but instead of collapsing down, atoms collide and fuse, releasing explosive atomic energy. Radiation pushes outwards against gravity, holding the star open as a glowing ball of gas. As stars age, more and more of the atoms are fused, creating heavier and heavier elements, and eventually the fuel starts to run out. Without the outwards push, the balance is tipped in favour of gravity and the star begins to collapse. For small stars, such as the Sun, the collapse is incomplete, and repelling forces manage to hold the last glowing embers open as a white dwarf star. For a white dwarf star that's larger than 1.4 times the mass of the Sun – known as the Chandrasekhar limit – these forces are insufficient. The star continues to crunch inwards, forming a dense neutron star or a black hole.

"As stars age, the fuel eventually starts to run out"

2 SUPERMASSIVE BLACK HOLES DON'T DESTROY EVERYTHING NEARBY

Actively feeding supermassive black holes are some of the most violent places in the universe, and quasars devour the equivalent of tens to thousands of Suns each year. Amazingly, though, the galaxies that surround them don't disappear into the abyss. Despite their frightening reputation, black holes don't actually behave that differently to other massive objects in the universe, unless you get too close. Just as Earth will not spontaneously crash into the Sun, objects in stable orbits around black holes are in no danger of being swallowed.



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3 BLACK HOLES SLOW THE FLOW OF TIME

To an outside observer, an object falling into a black hole appears to slow down before stopping, caught in suspended animation at the boundary.

4 A BLACK HOLE REVEALS NO CLUES ABOUT WHAT IT'S SWALLOWED

As matter enters a black hole, it's stretched, pulled and eventually shredded. Even if something were to leak out, it would bear no resemblance to what went in.

5 THEY HAVE NO SIZE LIMIT

In theory, black holes continue to grow in size indefinitely, but just how large they are able to get depends on their local environment.

6 AROUND THE SAME MASS AS THE SOLAR SYSTEM

Supermassive black holes contain the mass of at least 100,000 Suns compressed into a space that's around the same size as our Solar System.

7 IT'S THE SIZE OF A BLACK HOLE THAT MATTERS, NOT ITS MASS

Just a few micrograms of matter would be enough to create a black hole if it were compressed into a small enough space.

8 SOME GALAXIES MIGHT HARBOUR ULTRAMASSIVE ONES

The galaxy OJ 287 has two black holes, one of which is thought to contain the mass of around 18 billion Suns.

9 BLACK HOLES FEED ON STARS, REVEALING THEIR LOCATIONS

Black holes cannot be seen directly, but the effect they have on their surroundings often reveals their presence. In the Cygnus constellation, a blue supergiant star is being pulled into a teardrop shape, causing its light to flicker as it spins. The star orbits once every 5.6 days, and as it turns, the outer layer of gas is stripped away from its surface at 1,500 kilometres (932 miles) per second as it's funnelled to an invisible point.

The supergiant is part of a binary system and is locked in a fatal dance with a black hole known as Cygnus X-1. As the black hole spins, space and time spiral up with it, and dust and gas from the star accumulate in a vast swirling whirlpool known as the accretion disc. Particles spiral towards the event horizon, like water circling a drain, and as they tumble inwards the friction releases bright flashes and flares of X-ray light.

1

10 BLACK HOLES SPIN FASTER THAN THE STARS THAT MADE THEM

If a star is spinning when it dies, it will continue to spin if it becomes a black hole. However, it won't spin at the same speed. Imagine the star is a twirling ice skater, holding their arms outstretched. As they spin, they pull their arms inwards and start to spin faster. This is down to the law of conservation of angular momentum. As the matter collapses in towards the centre of a dying star, its diameter decreases – like the ice skater, it spins faster.

1 Companion star
Some stellar black holes are part of binary systems and are closely associated with another star.

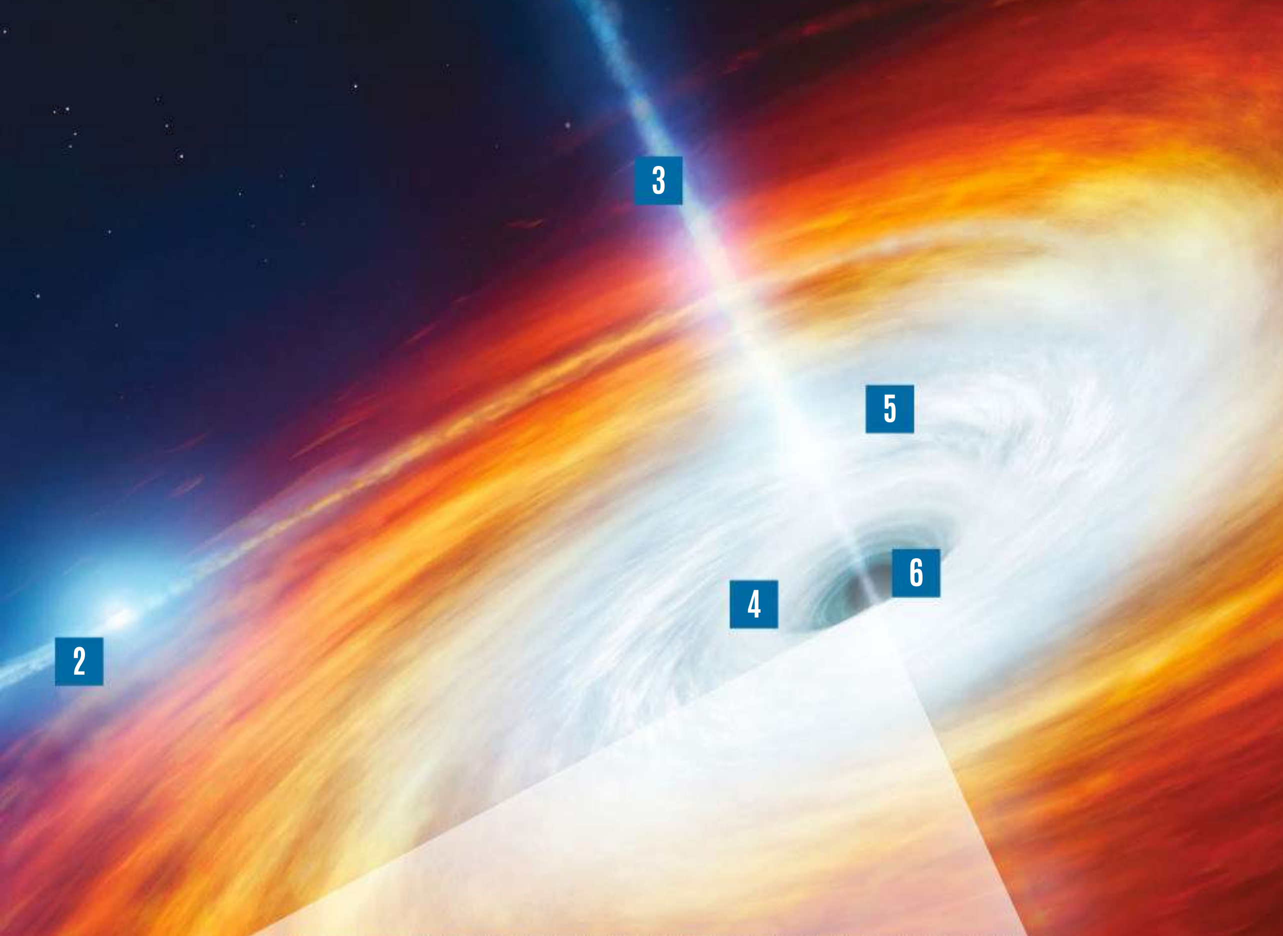
2 Magnetic field lines
As black holes spin, the magnetic fields within their accretion discs will spiral up and down, creating a doughnut-shaped field around them.

3 Jets
At the poles of a spinning black hole, the magnetic field funnels material away from the immense gravitational pull, shooting it out into space in bright jets.

4 Event horizon
The event horizon is the point of no return, where the velocity required to escape the pull of the black hole is greater than the speed of light.

5 Accretion disc
Spinning black holes trap a wide disc of matter that increases in velocity towards the event horizon. Particles rub against each other, glowing with energetic radiation.

6 Singularity
Shielded from view at the very heart of the black hole, matter is crushed to a single point. Physics as we know it falls apart, and space and time cease to exist.



11 THE CENTRE OF A BLACK HOLE COULD CONTAIN A SINGULARITY

The event horizon of a black hole can measure thousands of kilometres in diameter, but once matter crosses over the edge, it doesn't stop moving. Exactly what happens on the inside is debated, but according to Einstein's theory of general relativity, the curvature of space-time inside a black hole is extreme, and everything is directed towards a single point, known mathematically as a singularity. Every possible path leads back to the centre, and matter becomes so crushed into such a tiny space that it's unrecognisable. The singularity is infinitely small and infinitely dense, creating an infinite curvature in space-time. Within a region of space known as the event horizon, anything that crosses over is compelled towards the centre with no hope of escape.

12 SOME OF THEM HAVE JETS

Some black holes spew impressive amounts of energy from their poles, marking their location like a beacon. As dust and gas race towards the event horizon of a spinning black hole, magnetic field lines direct some of the energy outwards, funnelling it into two energetic jets, like a particle accelerator.

NASA's Wide-field Infrared Survey Explorer (WISE) identified a pair of black holes orbiting one another that together create gravitational and magnetic disturbances so intense that their jets are being warped and twisted into ribbon-like spirals.

13 THEY LEAK RADIATION

Stephen Hawking showed that black holes could actually radiate energy, known as Hawking radiation, releasing their scrambled contents back into the universe.

14 IT TAKES MILLIONS OF YEARS TO ORBIT OUR SUPERMASSIVE BLACK HOLE

Sagittarius A* lies around 26,000 light years from the Solar System. It takes 225 million years for us to complete a single orbit around the galactic centre of the Milky Way.

15 THEY WERE KNOWN AS DARK STARS

The idea of black holes has been around much longer than the science that predicts their existence, but in the 18th century they were known as 'dark stars'.

16 CYGNUS X-1 WAS THE VERY FIRST BLACK HOLE TO BE IDENTIFIED

Cygnus X-1 is one of the brightest radio sources in the sky and is currently in the process of devouring a blue supergiant.

17 THEY CREATE WAVES

Einstein predicted that as massive objects like black holes move through space, they create gravitational waves that ripple through space-time, now confirmed.

18 THE UNIVERSE IS SHAPED BY THEM

Supermassive black holes are found at the hearts of almost all large galaxies and act as the linchpins of the universe around which stars and planets turn.

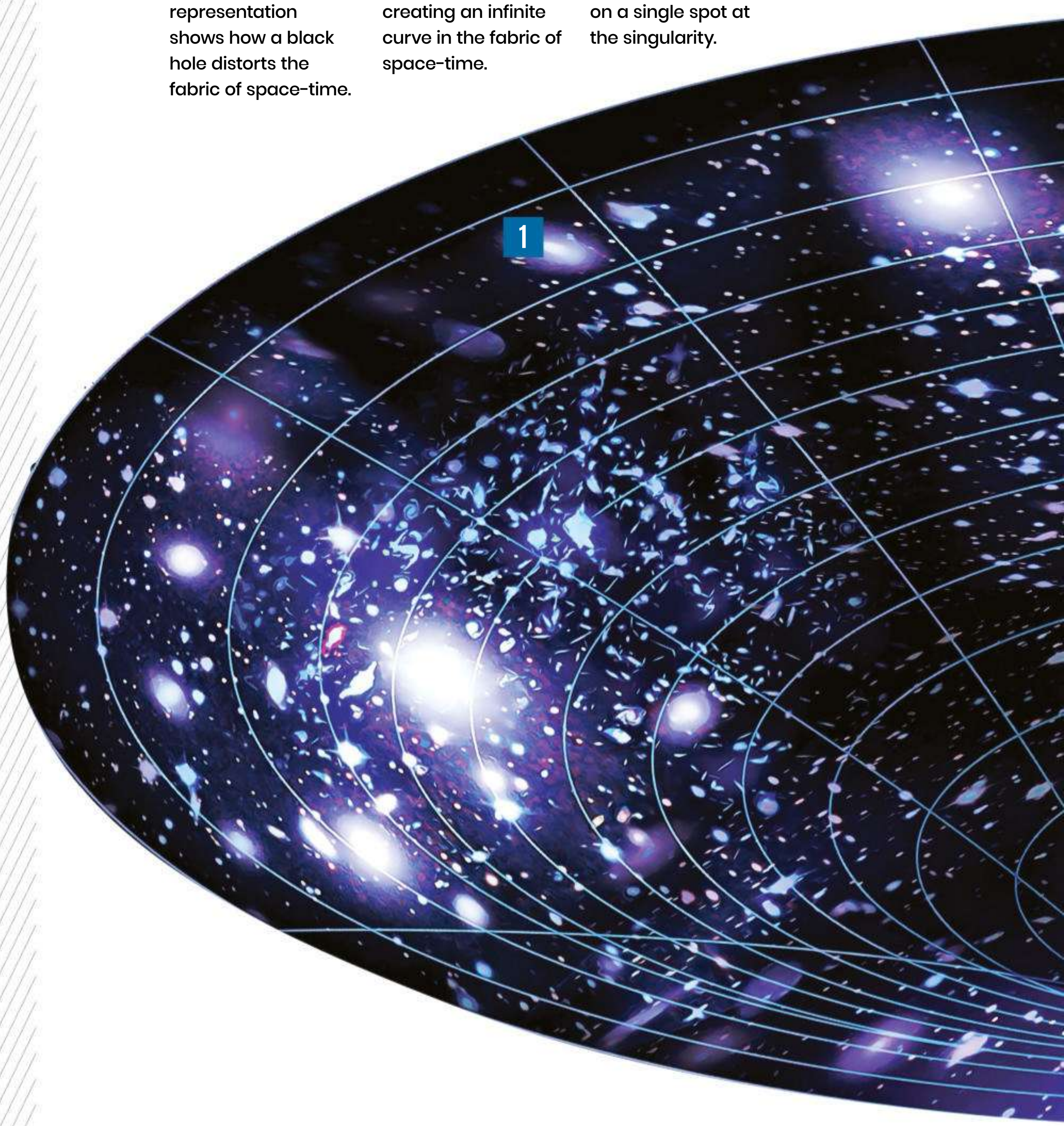
19 STELLAR BLACK HOLES CONTAIN THE MASSES OF FIVE OR MORE SUNS

Black holes formed during the death of a star usually contain at least as much mass as five Sun-sized stars, compressed into an area measuring just a few kilometres across.

1 Space-time This two-dimensional representation shows how a black hole distorts the fabric of space-time.

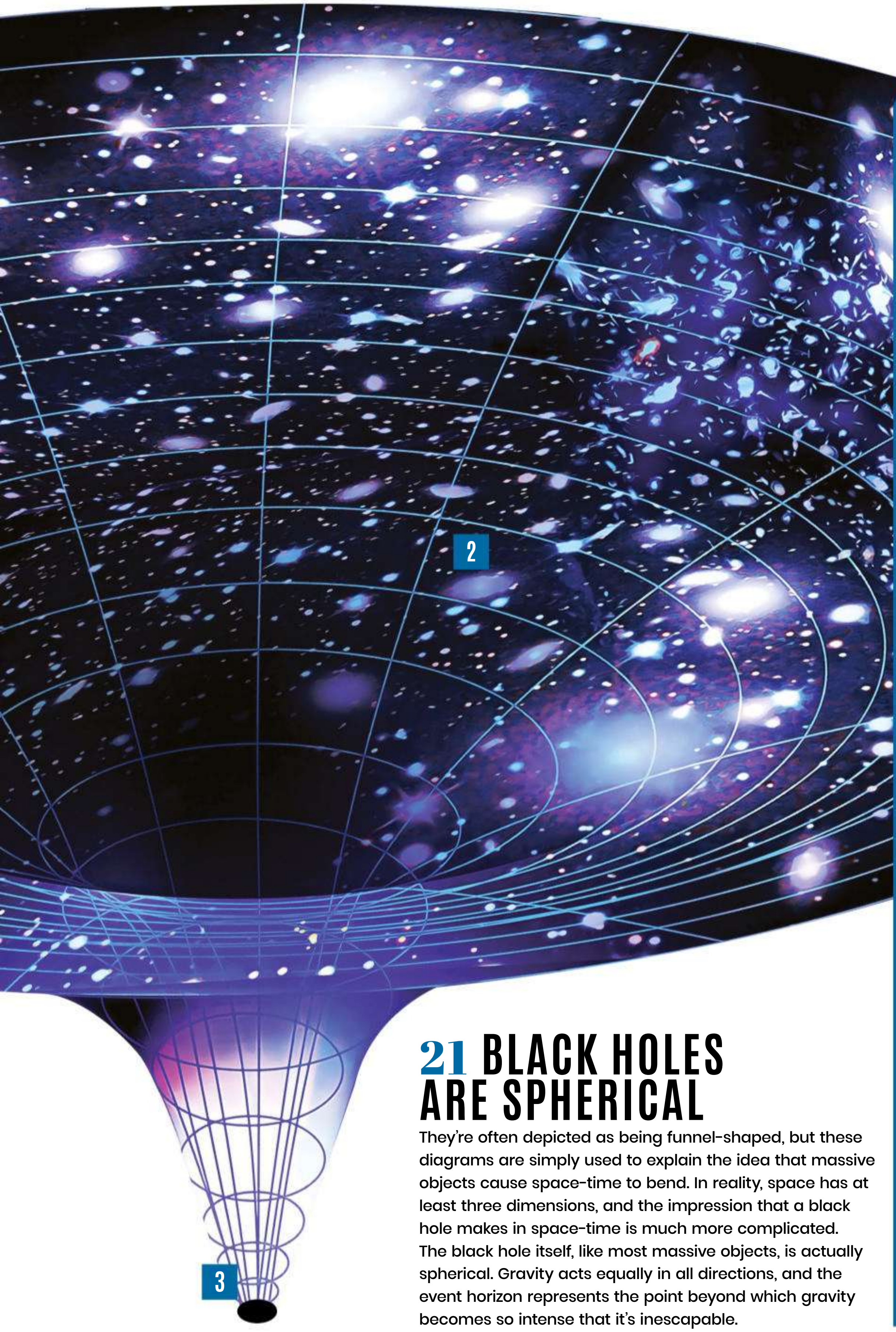
2 Infinite curve The singularity is infinitely dense, creating an infinite curve in the fabric of space-time.

3 Focal point Space and time are concentrated on a single spot at the singularity.



20 BLACK HOLES BEND SPACE-TIME

Einstein showed that the universe is made from a fabric known as space-time, and just like a piece of cloth, it can be bent, twisted and stretched. Massive objects, including planets and stars, make dips in the fabric of space-time, like bowling balls sitting on top of a trampoline. The more mass that's collected in one area, the more of an impression it makes in the fabric and the more energy is required to escape its gravitational field. One object in orbit around another can be thought of as being similar to a cyclist in a velodrome. The cyclist is trying to travel in a straight line. However, the curved floor forces them to move around in circles. If they pedal faster, they might be able to gather up enough speed to climb out of the top of the dome, and if they slow down they will start to drift back in towards the centre.



21 BLACK HOLES ARE SPHERICAL

They're often depicted as being funnel-shaped, but these diagrams are simply used to explain the idea that massive objects cause space-time to bend. In reality, space has at least three dimensions, and the impression that a black hole makes in space-time is much more complicated. The black hole itself, like most massive objects, is actually spherical. Gravity acts equally in all directions, and the event horizon represents the point beyond which gravity becomes so intense that it's inescapable.

We speak to Douglas Richstone of the University of Michigan about the origins of supermassive black holes

22 ALMOST EVERY GOOD-SIZED GALAXY HAS A SUPERMASSIVE BLACK HOLE

"For every galaxy that's reasonably good-sized and regular – that is, a galaxy with a disc and a bulge, and possibly spiral arms, or a so-called elliptical galaxy that looks round – there's a black hole. Moreover, the black hole's mass tracks the mass of the host galaxy and is about a thousandth of the galaxy's mass. These black holes range from 1 million to nearly 10 billion solar masses. However, for galaxies that are very small, irregular or possibly only have a disc and no round component, or bulge, the situation is much more complicated. Some of these galaxies appear to have black holes, while others don't."

23 QUIET SUPERMASSIVE BLACK HOLES USED TO BE QUASARS

"We don't know for certain how the biggest black holes form, but there is a clue. The amount of mass in galaxies at present tied up in black holes is almost exactly the amount of mass needed to power quasars [very bright objects thought to be black holes accreting matter] when the universe was about a fifth of its present age. It's reasonable to identify the black holes in galaxies now as the relics of quasars."

24 IT'S IMPOSSIBLE TO SEE THEM DIRECTLY

Black holes do not emit or reflect any electromagnetic radiation except Hawking radiation, but their gravitational effects are detectable.

25 SOME BLACK HOLES SPIN AT HALF THE SPEED OF LIGHT

By looking at the pattern of X-rays in the area surrounding a black hole, the speed at which it's spinning can be determined.

26 THERE ARE TWO DIFFERENT TYPES OF BLACK HOLE

Schwarzschild black holes are the simplest and are made up of just an event horizon and a singularity. Kerr black holes rotate and have a third component known as the ergosphere.

27 BLACK HOLES ARE NOISY

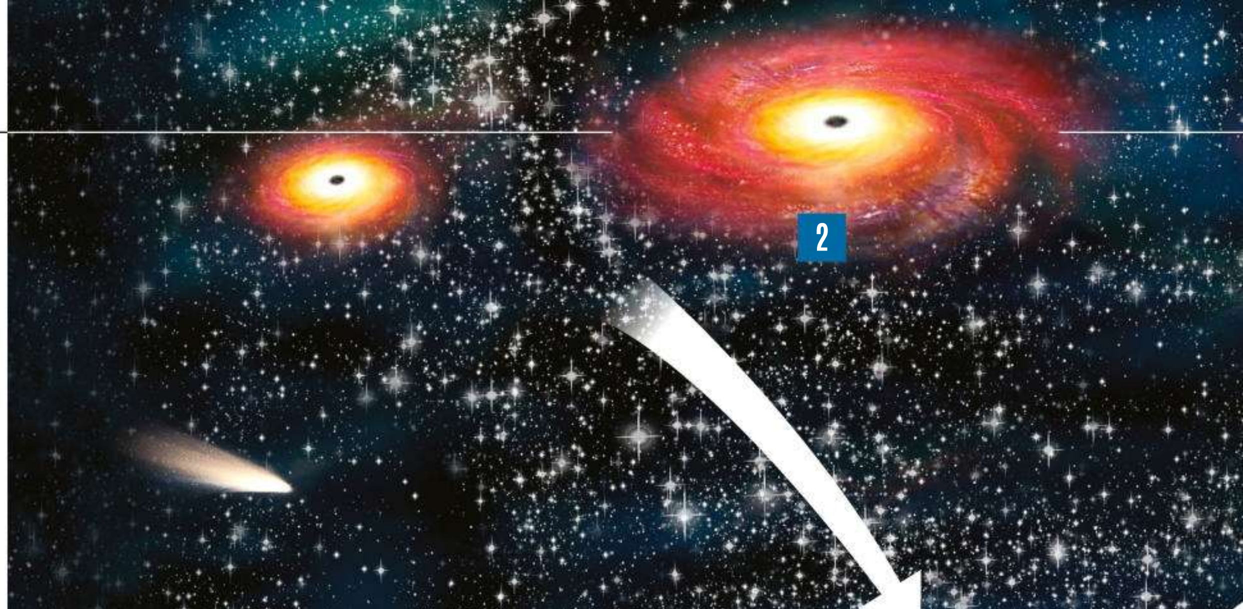
In 2003, NASA's Chandra X-ray Observatory revealed that a black hole in the Perseus Cluster makes a sound in the pitch of B flat.

28 WE'LL NEVER KNOW WHAT'S REALLY INSIDE A BLACK HOLE

Light cannot escape across the event horizon of a black hole, preventing us from ever seeing inside one. There's also no definitive answer about what really happens inside a black hole.

29 ONE DAY, BLACK HOLES WILL DOMINATE THE UNIVERSE

Black holes evaporate so slowly that they will exist long after the last of the stars fade and die, leading scientists to predict that one day they will be all that's left in the universe.



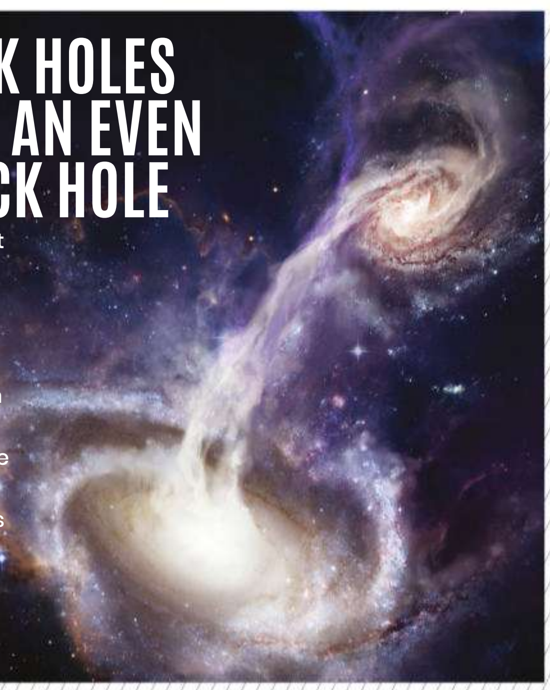
30 OBJECTS ARE STRETCHED LIKE SPAGHETTI AS THEY APPROACH A BLACK HOLE

3

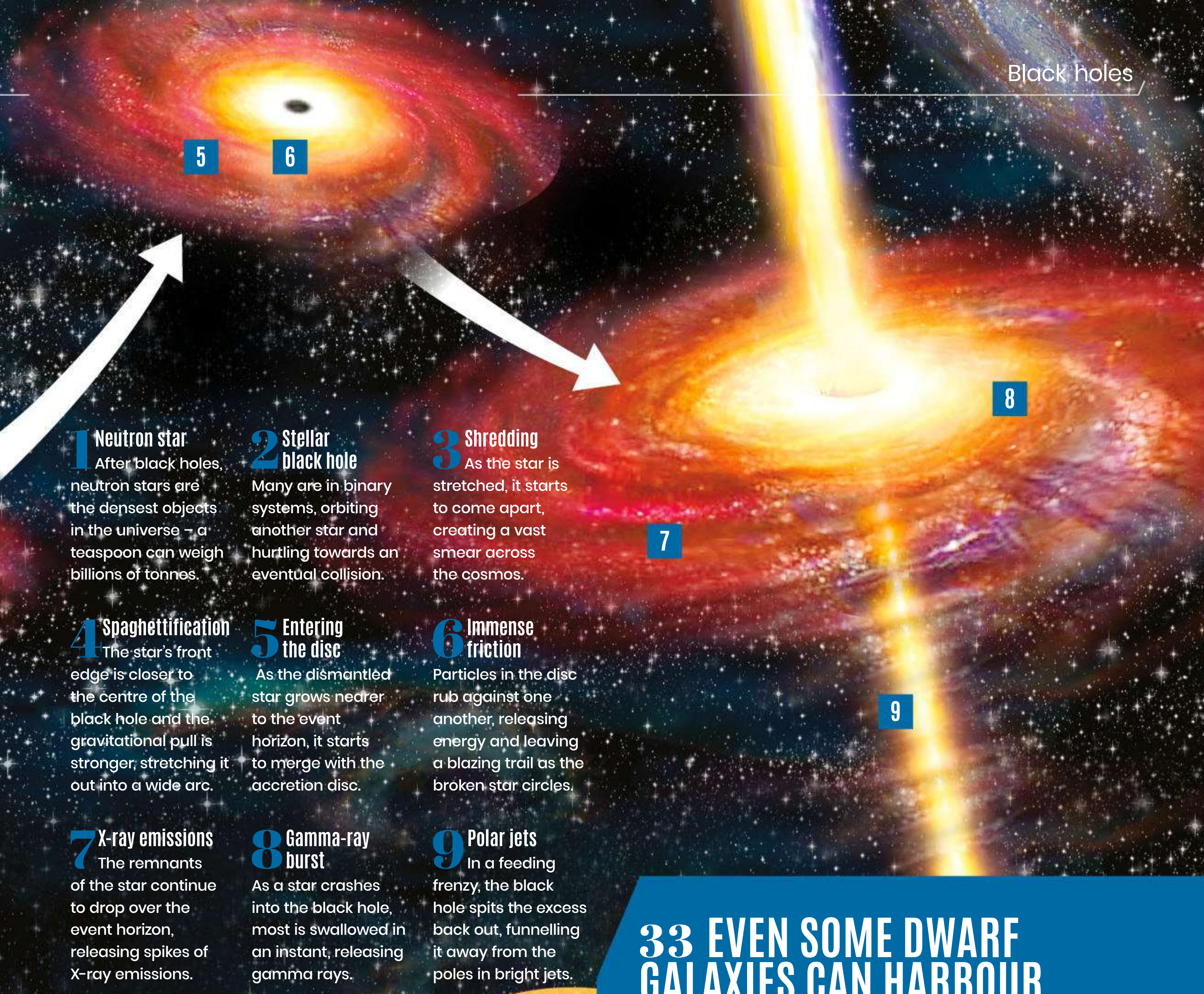
4

As an object gets closer to a black hole, the gravitational pull rises sharply. The parts of the object that are closest to the black hole experience stronger attraction than those farther away, causing them to accelerate faster. This stretches the object as the front moves more quickly than the back, drawing it out into a long filament in a process known as spaghettification. The tidal forces around a black hole are strong enough that anything entering becomes stretched, from the largest stars to the smallest atoms. When the stretching force exceeds the elastic limit of the material, it starts to break apart, tearing into smaller and smaller pieces, each being stretched out until all that's left are elementary particles. Spaghettification takes place at different times depending on the size and type of black hole. For small stellar black holes, for example, it occurs before objects have crossed the event horizon. However, in supermassive black holes the tidal forces don't always become great enough until the object has crossed over the point of no return.

31 WHEN TWO BLACK HOLES COLLIDE, THEY FORM AN EVEN MORE MASSIVE BLACK HOLE



It's likely that the supermassive black holes at the centres of galaxies began to form early in the evolution of the universe. As matter condensed to form the first galaxies, it would have been much closer together, and small black holes would have been able to feast on dust and gas, becoming truly massive in a very short space of time. Several intermediate black holes are thought to have formed within clusters of stars before sinking towards the centres of galaxies under the influence of each other's gravitational pull, collapsing in on one another to form the supermassive giants that we see today.



1 Neutron star
After black holes, neutron stars are the densest objects in the universe – a teaspoon can weigh billions of tonnes.

2 Stellar black hole
Many are in binary systems, orbiting another star and hurtling towards an eventual collision.

3 Shredding
As the star is stretched, it starts to come apart, creating a vast smear across the cosmos.

4 Spaghettification
The star's front edge is closer to the centre of the black hole and the gravitational pull is stronger, stretching it out into a wide arc.

5 Entering the disc
As the dismantled star grows nearer to the event horizon, it starts to merge with the accretion disc.

6 Immense friction
Particles in the disc rub against one another, releasing energy and leaving a blazing trail as the broken star circles.

7 X-ray emissions
The remnants of the star continue to drop over the event horizon, releasing spikes of X-ray emissions.

8 Gamma-ray burst
As a star crashes into the black hole, most is swallowed in an instant, releasing gamma rays.

9 Polar jets
In a feeding frenzy, the black hole spits the excess back out, funnelling it away from the poles in bright jets.

32 THE LARGER THE BLACK HOLE, THE LESS DENSE IT IS

If the mass inside a black hole doubles, the volume of its event horizon increases eight times, making it more massive, but less dense.

The sponge is bigger and more massive. but less dense than the marble

33 EVEN SOME DWARF GALAXIES CAN HARBOUR SUPERMASSIVE BLACK HOLES

Anil Seth of the University of Utah discovered a supermassive black hole at the centre of a dwarf galaxy

What makes the black hole in the dwarf galaxy M60-UCD1 such an interesting find?
We think most big galaxies have supermassive black holes, but M60-UCD1 is much smaller and less massive than any other galaxy with one. Supermassive black holes play an important role in how galaxies form, and this provides a new environment for us to find these objects.

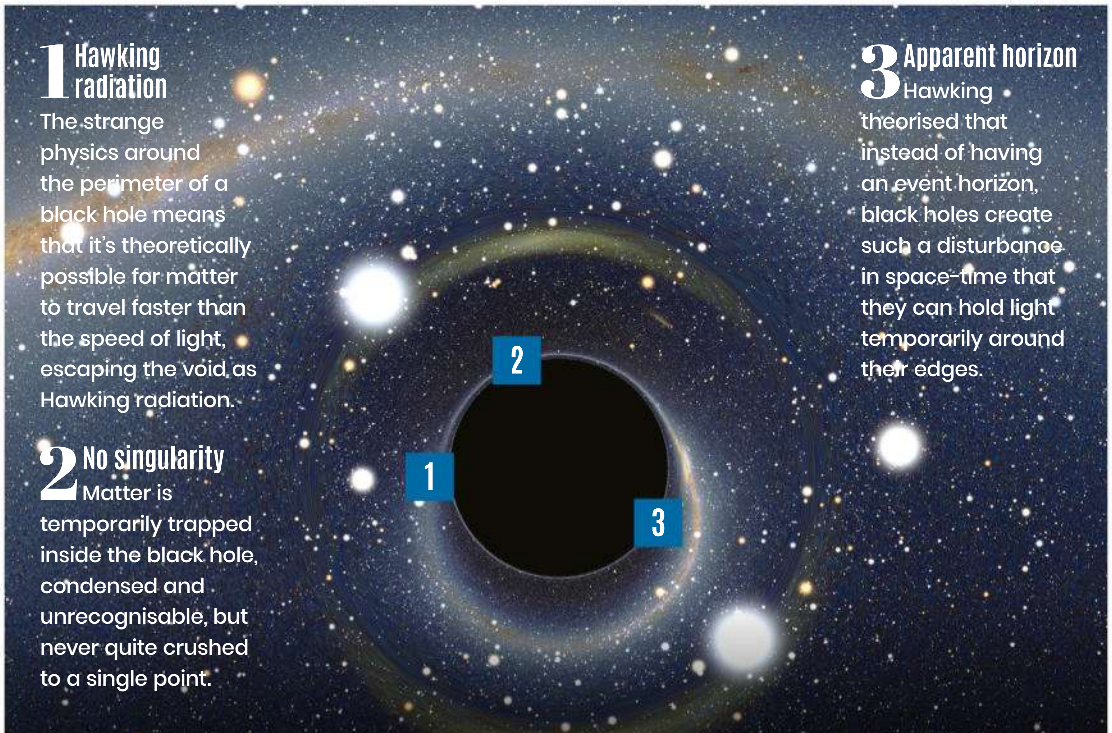
Currently, we don't understand how supermassive black holes form because their formation happened early in the universe.

How did such a big black hole form in such a small galaxy?
M60-UCD1 got its name because it's just 22,000 light years from the giant elliptical galaxy Messier 60. We think that M60-UCD1 is in orbit around Messier 60 and was once a much larger galaxy. When it passed close to the centre of Messier 60, this once-bigger galaxy had its outer parts stripped away, leaving just the dense core of stars and the black hole behind.

34 BLACK HOLES WERE FIRST IMAGINED IN THE 18TH CENTURY

John Michell and Pierre-Simon Laplace were the first to wonder about the existence of black holes, imagining that beyond a certain point, the gravity of a massive object must become so great that nothing can get away. The trouble was that according to Newton's theory of gravitation, light wouldn't be affected by gravity because it has no mass. So no matter how massive an object became, light should be able to escape. It wasn't until Einstein's theory of general relativity that the physics of black holes really started to make sense.

> "Beyond a certain point, the gravity of a massive object must become so great nothing can get away"



1 Hawking radiation

The strange physics around the perimeter of a black hole means that it's theoretically possible for matter to travel faster than the speed of light, escaping the void as Hawking radiation.

2 No singularity

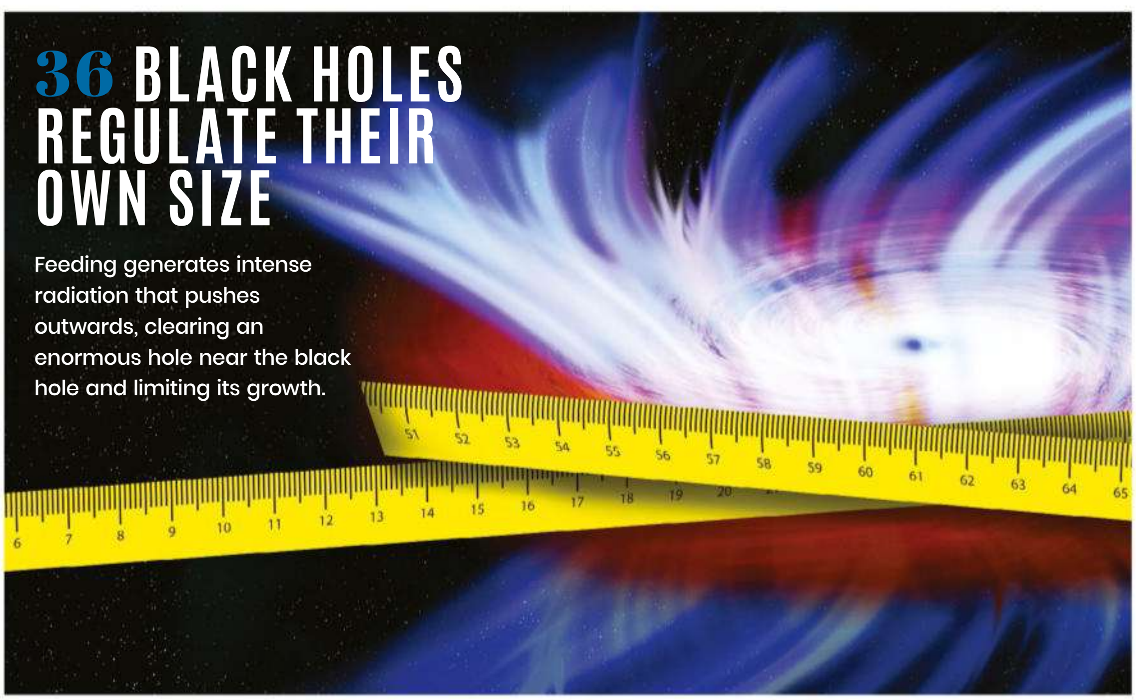
Matter is temporarily trapped inside the black hole, condensed and unrecognisable, but never quite crushed to a single point.

3 Apparent horizon

Hawking theorised that instead of having an event horizon, black holes create such a disturbance in space-time that they can hold light temporarily around their edges.

35 BLACK HOLES MIGHT NOT EXIST

In 2014, Stephen Hawking put forward a controversial theory: they don't exist at all, at least not in the way we imagine them. The science of black holes is based on Einstein's theory of general relativity, but there are grey areas. One of the major problems is the event horizon. According to Einstein, it's the point at which matter crosses over into a black hole and gets destroyed as it's pulled towards the singularity. But according to quantum theory, the event horizon would actually be a 'firewall' of high-energy particles. The physics behind Einstein's theory contradict that of quantum theory. Hawking proposed the event horizon doesn't actually exist. Black holes are not bottomless pits from which nothing can return, and that instead they just temporarily hold and scramble matter before releasing it back into the universe as radiation.

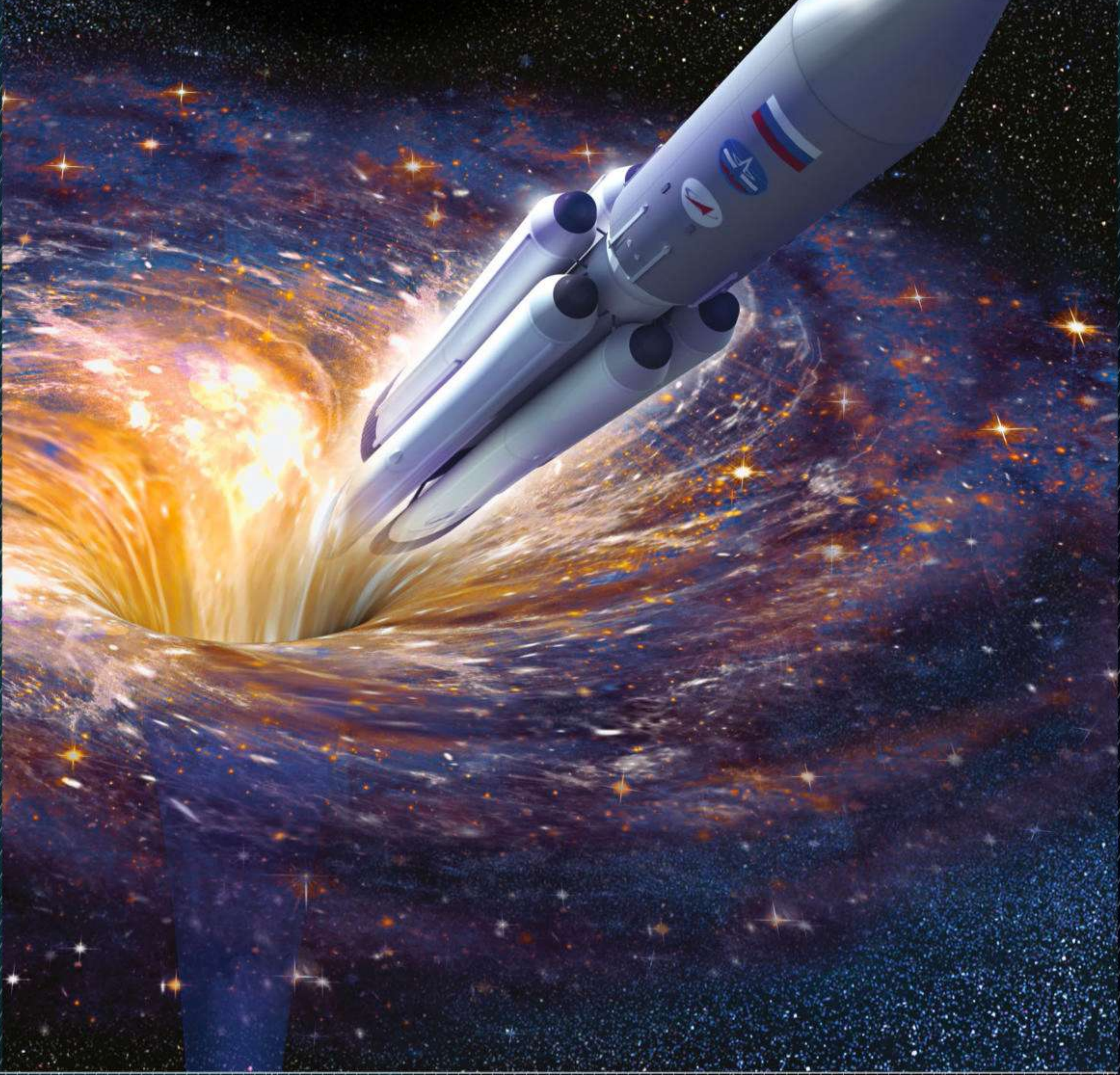


36 BLACK HOLES REGULATE THEIR OWN SIZE

Feeding generates intense radiation that pushes outwards, clearing an enormous hole near the black hole and limiting its growth.

37 EVEN A ROCKET TRAVELLING AT THE SPEED OF LIGHT COULDN'T ESCAPE FROM A BLACK HOLE

As objects become more massive and more dense, it becomes increasingly hard to escape their gravitational pull. For a rocket to escape the gravity of Earth, it must travel at a speed of 11.2 kilometres (6.9 miles) per second. From the surface of the Sun that speed rises to 618 kilometres (1,005 miles) per second, and from a dense white dwarf star like Sirius B, the same rocket would need to travel at 5,200 kilometres (3,231 miles) per second in order to escape. Within the grip of a black hole, even a rocket travelling at the breakneck speed of light, or 299,792 kilometres (186,282 miles) per second, would be unable to free itself from the immense gravitational pull.



38 SOME CAN BE TINY

The smallest theoretical mass for a black hole is around 22 micrograms, a value known as Planck mass.

39 THE CLOSEST KNOWN BLACK HOLE IS 1,560 LIGHT YEARS AWAY FROM EARTH

The closest black hole to Earth is Gaia BH1 in Ophiuchus. It has the mass of about 9.6 Suns.

40 BLACK HOLES HAVE NO HAIR

This famous statement made by scientist John Wheeler describes the simplicity of black holes. Typically, they can be described by just three quantities: their mass, angular momentum and electric charge.

41 THEY HALT LOCAL STAR FORMATION

The largest and most active supermassive black holes often occur in the quietest galaxies. The radiation released as they feed stops the gas around them condensing to form stars.

42 THE SUN COULD NEVER BECOME A BLACK HOLE

To become a black hole, a star must be so massive that it completely collapses under its own gravitational pull. The Sun is much too small, and instead it will end its life as a white dwarf.

43 BLACK HOLES COME IN DIFFERENT SIZES

Stellar-mass black holes can measure just a few kilometres in diameter, whereas supermassive black holes can be the size of our Solar System.

44 THERE'S A SUPERMASSIVE BLACK HOLE AT THE CENTRE OF THE MILKY WAY

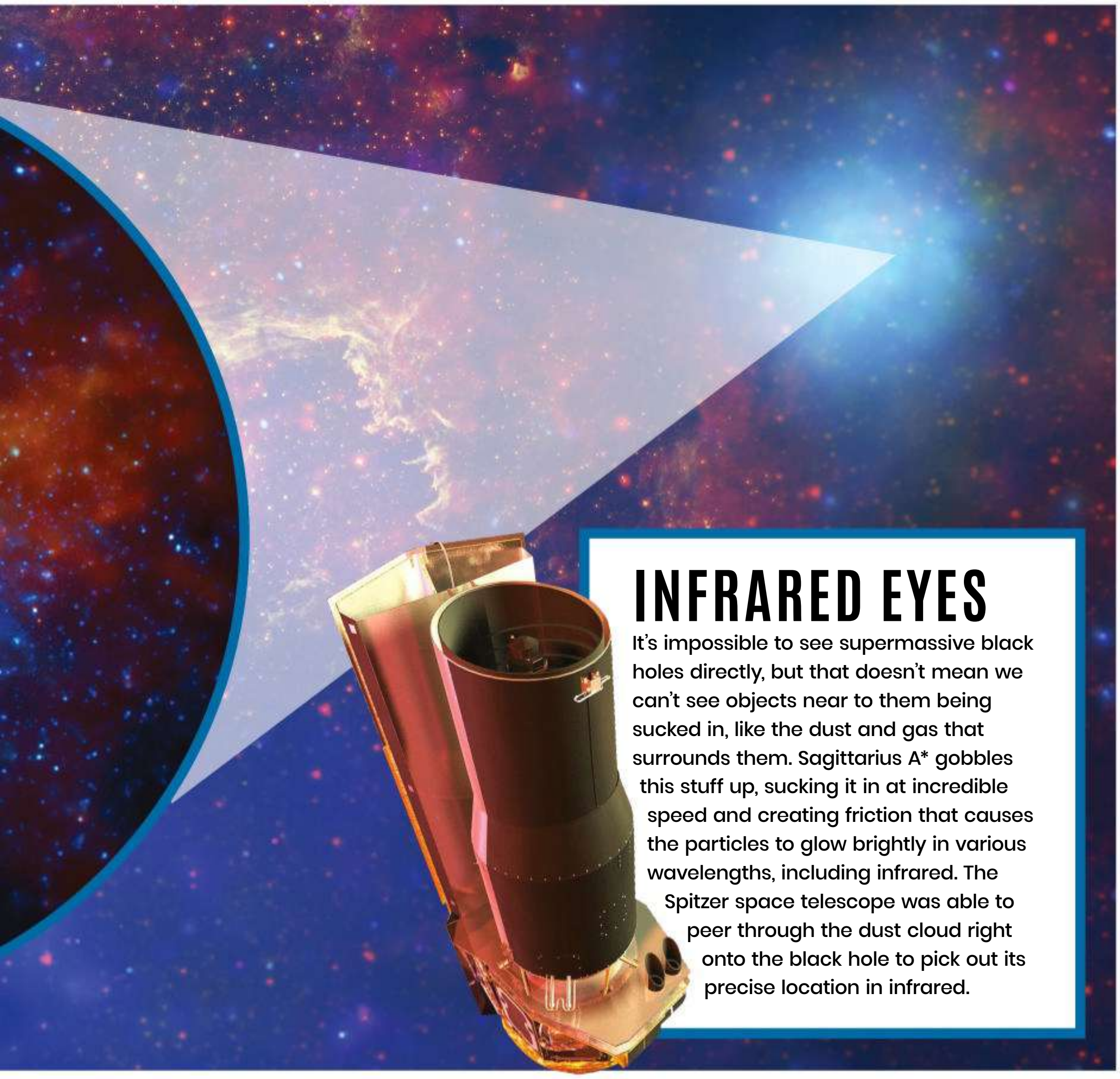
At the centre of the Milky Way, the stars move in strange circles. They hurtle towards a bright radio source, turn in a tight hairpin and then race away again. Tracing the lines of their orbits reveals that they all overlap at a single point, known as Sagittarius A*.

The region is shrouded in a thick cloud of dust and gas, making it difficult to see, but in order to account for these highly elliptical orbits, astronomers have calculated that Sagittarius A* must contain around 4 million solar masses, compressed into a volume with a radius of about 25 million kilometres (15.5 million miles).

Strange things happen around supermassive black hole Sagittarius A*

45 SOME BLACK HOLES POWER THE BRIGHTEST OBJECTS IN THE UNIVERSE

In the 1960s, astronomer Allan Sandage noticed a very bright object in the distant sky. It was as bright as a nearby star, but its vast distance meant it must be emitting hundreds of times as much energy as all of the stars in the Milky Way. Dubbed quasars, these objects are among the brightest in the universe and represent actively feeding supermassive black holes. Thousands have been identified, and each blazes brightly as matter tumbles onto its accretion disc, spewing X-rays and visible light into space.



INFRARED EYES

It's impossible to see supermassive black holes directly, but that doesn't mean we can't see objects near to them being sucked in, like the dust and gas that surrounds them. Sagittarius A* gobbles this stuff up, sucking it in at incredible speed and creating friction that causes the particles to glow brightly in various wavelengths, including infrared. The Spitzer space telescope was able to peer through the dust cloud right onto the black hole to pick out its precise location in infrared.

46 PARTICLE ACCELERATORS COULD CREATE MICROSCOPIC BLACK HOLES

When the Large Hadron Collider was switched on in 2008, there were concerns among scientists that the particles, travelling at close to the speed of light, could theoretically produce miniature black holes. So far, no such holes have been created, but it's definitely possible in theory. Even if a microscopic black hole was created, there would be little to worry about. The black hole would be so small that it would take billions of years for it to consume just one gram of matter.

47 SPACE AROUND A SPINNING BLACK HOLE IS WARPED

Spinning black holes distort space-time, wrapping it into a swirl known as the ergosphere. Within this area, space itself moves faster than the speed of light.

48 W49B IS THE YOUNGEST KNOWN IN THE MILKY WAY

A supernova remnant is all that remains of a star that exploded 1,000 years ago. There's no evidence of a neutron star at its core, leading astronomers to believe that it harbours a young black hole.

49 SPINNING BLACK HOLES HAVE A DOUGHNUT-SHAPED MAGNETIC FIELD FORMATION

As matter swirls around the accretion disc of a black hole, the magnetic fields line up, forming a doughnut-shaped ring with the event horizon nestled at the centre.

50 SMALLER GALAXIES CONTAIN MEDIUM-SIZED BLACK HOLES

It was originally thought that black holes only came in two sizes: stellar-mass black holes and supermassive black holes. However, researchers using data from NASA's Chandra X-Ray Observatory and Rossi X-Ray Timing Explorer (RXTE) were able to measure a medium-sized black hole in Messier 82 to be around 400 solar masses. Known as intermediate-mass black holes, these seeds of the most destructive objects in the universe contain between 100 and 10,000 times the mass of the Sun.

FOCUS ON

X-RAY VIEW SHOWS HOW SUPERMASSIVE BLACK HOLES SPEED UP PARTICLES IN JETS

Blazars are powered by immensely active galactic centres that fire beams of particles into space

Reported by Keith Cooper

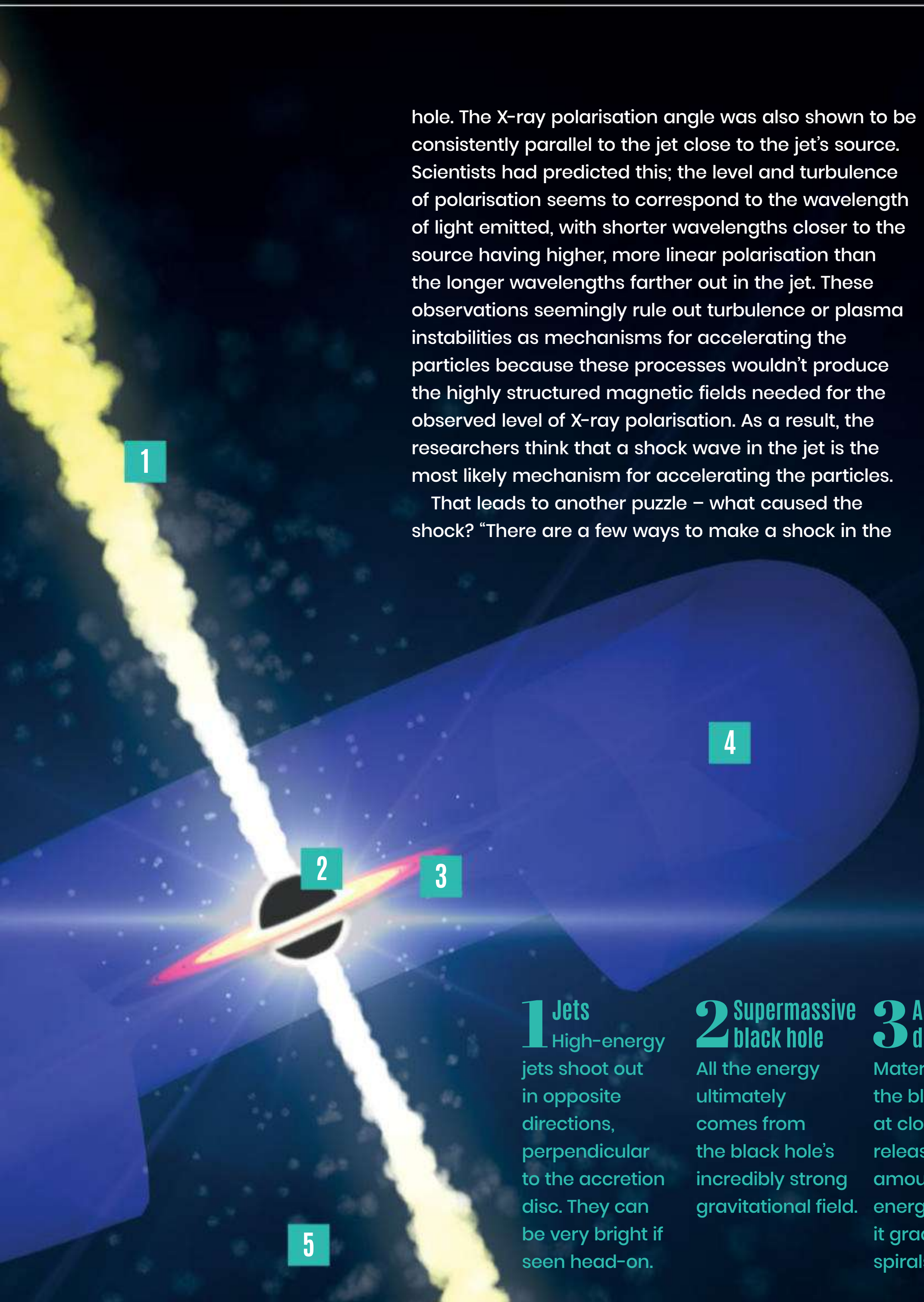
Peering deep into the heart of a blazar, astronomers have learned how particles are being accelerated to close to the speed of light, racing away in a jet emanating from near the blazar's monstrous supermassive black hole. Blazars are quasars seen head-on; a quasar is an extremely active galactic nucleus (AGN) that is powered by a black hole accreting vast amounts of matter. The matter circles around the black hole in an accretion disc, where conditions are so extreme that the disc shines at millions of degrees. Tightly entwined magnetic fields wrapped up in the disc are able to funnel away some of the material in tightly collimated jets shooting away from the centre of the accretion disc in either direction. The charged particles in these jets spiral around the magnetic field lines, emitting something called synchrotron radiation. It's this radiation that produces most of the light that we see shining from quasars and blazars, in which one of the jets points towards Earth.

Astronomers have used NASA's Imaging X-ray Polarimetry Explorer (IXPE) satellite, which launched in December 2021, to observe the blazar Markarian 501, located about 456 million light years away from Earth. IXPE is particularly talented at observing the polarisation of light, which refers to the orientation in which light waves are seen to preferentially oscillate. In a blazar, the polarisation is influenced by the strength and structure of the blazar jet's magnetic field. IXPE's observations can shed light on the blazar's magnetic environment, which in turn can provide clues as to what's accelerating the particles in the jets.

If turbulence or instabilities in the jet were giving energy to the particles, scientists would expect the polarisation to be weak and at random angles, indicating a relatively disorganised magnetic field. But previous measurements of the polarisation at optical and radio wavelengths have only been sensitive to the parts of the jet farther away from the black hole, seeing the particles days or even weeks after they have been accelerated – too late to be conclusive. However, X-rays are produced closer to the source of acceleration, and their polarisation is indicative of whatever mechanism is accelerating the particles in the jet. "How close the X-rays we see with IXPE are depends on the spectrum of the source, but in any case they are very close," Ioannis Liodakis, an astronomer at the University of Turku in Finland and lead author of the new research, said.

The Markarian 501 observations, made in March 2022, measured the level of X-ray polarisation to be ten per cent, which is about twice as much as seen in optical light farther up the jet, away from the black

A blazer as seen head-on to Earth



hole. The X-ray polarisation angle was also shown to be consistently parallel to the jet close to the jet's source. Scientists had predicted this; the level and turbulence of polarisation seems to correspond to the wavelength of light emitted, with shorter wavelengths closer to the source having higher, more linear polarisation than the longer wavelengths farther out in the jet. These observations seemingly rule out turbulence or plasma instabilities as mechanisms for accelerating the particles because these processes wouldn't produce the highly structured magnetic fields needed for the observed level of X-ray polarisation. As a result, the researchers think that a shock wave in the jet is the most likely mechanism for accelerating the particles.

That leads to another puzzle – what caused the shock? "There are a few ways to make a shock in the jet," Liodakis said. "Based on our limited understanding, two ways are common. The first has to do with environmental reasons – changes in pressure and density of the external medium can lead to the creation of shocks. The second way is to have plasma moving at different velocities, and a shock can be created when a slow region collides with a faster one." If the shock theory is correct, scientists predict that at X-ray wavelengths, the polarisation angle will rotate; future observations with IXPE may be able to detect these rotations and support the team's conclusions.

The new X-ray results, in combination with the previous optical and radio polarisation measurements of Markarian 501's jet, show how important multi-wavelength observations are for getting a complete picture of what's going on. Similarly, earlier this year the Event Horizon Telescope measured the radio polarisation of another blazar jet, finding it to be corkscrew-shaped. Now, with IXPE's X-ray capabilities, astronomers have the tools to scrutinise blazar and quasar jets at all scales to better understand how the universe's ultimate particle accelerators function.

1 Jets High-energy jets shoot out in opposite directions, perpendicular to the accretion disc. They can be very bright if seen head-on.

2 Supermassive black hole All the energy ultimately comes from the black hole's incredibly strong gravitational field.

3 Accretion disc Material orbiting the black hole at close range releases huge amounts of energy as it gradually spirals in.

4 Dusty torus The accretion disc is surrounded by a larger, doughnut-shaped region of dust-like material that can obscure the view.

5 Viewing How much activity an observer actually sees depends on their viewing angle relative to the disc, torus and jets.

SUPERMASSIVE EXAMPLES

Leo I Dwarf Galaxy

Although this tiny galaxy is only about 20 million solar masses in total, its central black hole is proportionately huge at around 3 million solar masses.

Centaurus A

This huge elliptical galaxy, just 13 million light years away, is a powerful radio emitter thanks to the 55-million-solar-mass black hole at its centre.

NGC 7727

The product of two merging galaxies, NGC 7727 still retains two supermassive black holes, of 154 and 6.3 million solar masses, 1,600 light years apart.

Abell 2261

This cluster of galaxies is estimated to have a black hole of up to 100 billion solar masses near its centre. Its exact location continues to elude detection.




IS THE UNIVERSE DUE ANOTHER BIG BANG?

New theories and observations are shedding fresh light on the very beginnings of the cosmos, and the formation of the first stars and galaxies. But they're also revealing new and unexpected mysteries

Reported by Giles Sparrow

Ask any astronomer about the very beginnings of the universe, and they're likely to describe the Big Bang theory. Some 13.8 billion years ago, they'll say, the universe was born out of nothing, in an explosion that unleashed the expanding dimensions of space and time, alongside vast amounts of energy. In the moments that followed, most of this energy transformed into the building blocks of matter – subatomic particles of varying mass and complexity, which eventually came together to form simple atoms, and then coalesced to create giant, short-lived stars and the nuclei of the first galaxies.

There's a wealth of evidence to show that the Big Bang theory is broadly correct. For instance, even today the universe is still growing at tremendous speed, with widely separated galaxies and galaxy clusters being pulled apart as the space between them expands. What's more, when powerful telescopes focus on the galaxies farthest from Earth (whose light set out on its journey towards us many billions of years ago), they see violent star systems still in the process of formation. Most tellingly of all, the entire universe is filled with the weak 'afterglow' of the Big Bang itself – the Cosmic Microwave Background Radiation (CMBR) that comes from all over the sky and is otherwise inexplicable.

But even if the basics of the Big Bang are well established, that doesn't mean there aren't still questions to answer. The biggest mysteries of all lie at either end of the process – at the moment when space and time were supposedly 'created', and a few hundred million years later, in the period when the first stars and galaxies began to form. On Christmas Day 2021, NASA's enormous James Webb Space Telescope blasted off on a European Space Agency Ariane V rocket, with a mission to answer at least some of these big questions. The Webb's vast mirror is designed to capture infrared radiation with longer wavelengths (and less energy) than visible light. This includes radiation from the most distant (and therefore earliest) stars and galaxies, emitted as visible light but stretched into the infrared during its long journey across ever-expanding space. This shifting of light into the infrared means the earliest period of cosmic evolution is beyond the limits of instruments such as the Hubble Space Telescope, which work mostly in visible light, so Webb is bringing a whole generation of early galaxies into view – with surprising results.

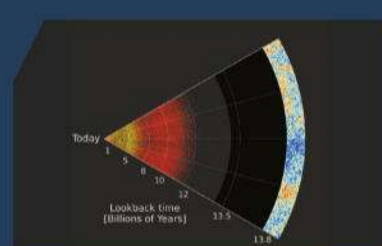
Astronomers have long assumed that galaxies develop in size and shape over time. Large spiral galaxies like our Milky Way are thought to have developed their structure after countless mergers between smaller irregular galaxies, while huge balls of stars known as elliptical galaxies appear to be the result of mergers and collisions between spirals. For this reason and others, the first galaxies that formed are assumed to have been very small, lightweight and faint.

Yet when Webb trained its arsenal of instruments on a small patch of sky close to the famous Big Dipper star pattern for many hours, it revealed something surprising. Hidden within the 'deep field' image, Dr Erica Nelson of the University of Colorado Boulder found half a dozen galaxies that were both extremely red – and therefore distant and very early in cosmic history – and unusually bright. If the brightness of the galaxies is a good indication of their mass (as it usually is) then it seems that some of these bright early galaxies could be as heavy as our own Milky Way. "It's bananas," says Nelson. "You just don't expect the early universe to be able to organise itself that quickly. These galaxies should not have had time to form."

The discovery is so surprising, in fact, that some astronomers have nicknamed the new discoveries "universe breaker" galaxies. That's because they threaten to undermine a highly successful standard model used for understanding large-scale cosmic evolution. Known as Lambda-CDM, this model balances the strength of dark energy – a mysterious force that accelerates the rate of expansion of space, represented by the Greek letter Lambda – against the gravitational attraction of cold dark matter, the invisible and transparent material that vastly outweighs normal matter in the universe, and can only be detected through its gravitational influence. Dark matter's

COSMIC TIME MACHINE

Because even light has a speed limit, powerful telescopes can act as cosmic time machines, allowing astronomers to look back across the history of the Universe. This map from the Sloan Digital Sky Survey charts relatively nearby galaxies and galaxy clusters (yellow) and more distant but bright quasars (red) in terms of their 'lookback time' – the amount of time their light has travelled to reach us. Between the most distant quasars and the 'cosmic dark age' before galaxies began to form lies the mysterious zone of galaxies whose light has been stretched beyond the visible range – the region now being probed by the Webb.



unusual properties allowed it to begin coalescing and forming structures within the expanding incandescent fireball of the early universe, at a time when normal matter was still unable to clump together. The result was a pattern of 'ripples', tiny variations in the density of the universe, imprinted on the CMB that escaped across space as the fireball cleared about 380,000 years after the Big Bang. In the long 'cosmic dark age' that followed, gravity from the ripples attracted the normal matter that eventually formed the first stars and galaxies.

Computer simulations have demonstrated that, with certain parameters for the behaviour of both dark energy and dark matter, Lambda-CDM results in a Universe very like the one we see today, However the model also predicts that an early generation of small galaxies that took a billion years or more to merge and form more substantial systems. A recent study by Dr Mike Boylan-Kolchin, an associate professor at the University of Texas at Austin showed that the massive galaxies seen in the Webb push at the uppermost limits of what's permitted by Lambda-CDM, and predicted that many more 'universe breakers' are likely to be discovered elsewhere in the sky. "If the masses are right, then we are in uncharted territory," Boylan-Kolchin says. "We'll require something very new about galaxy formation or a modification to cosmology."

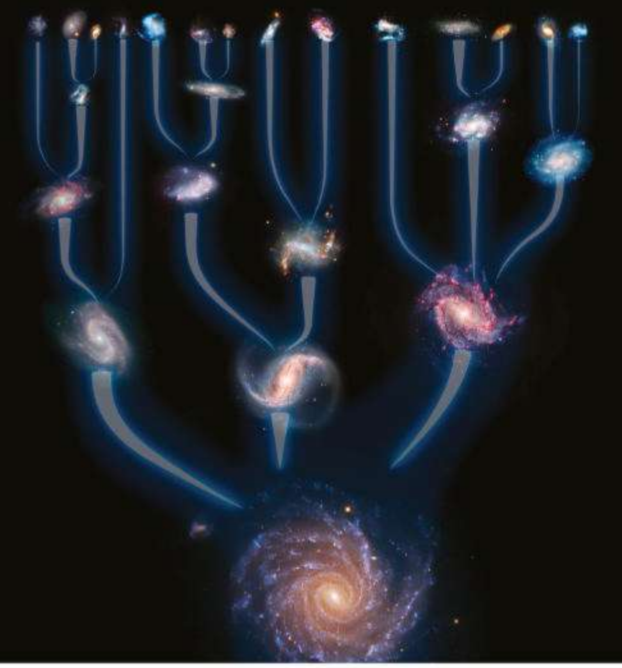
One way to resolve the puzzle would be if the rules of galaxy formation were somehow different in these ancient times; if early galaxies incorporated much more of their available matter into stars, this would allow them to appear brighter even if they were relatively small and lightweight by today's cosmic standards. "Another possibility is that these things are a different kind of weird object, such as faint quasars," suggests Nelson. In this scenario, the galaxies' excess brightness would be due not to their stars, but to the activity of supermassive black holes within them, feeding on gas and dust from their immediate surroundings and emitting radiation in a similar but much more restrained way to the violent active galaxies known as quasars.

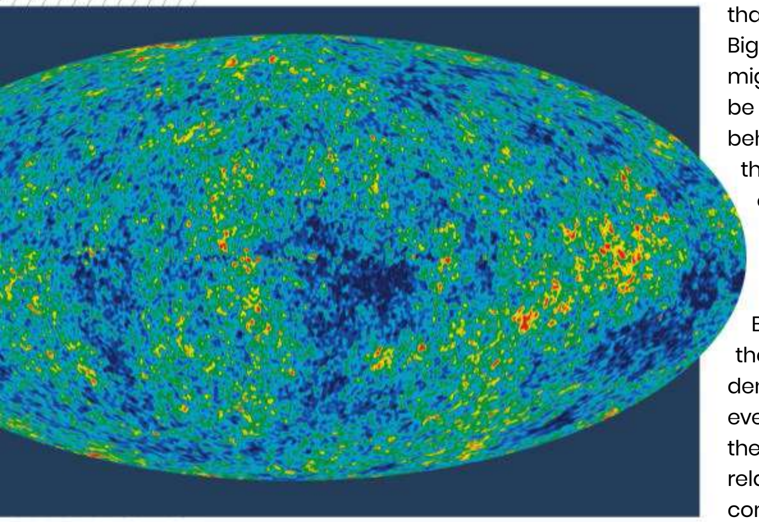
One other alternative explanation for the galaxies is even more intriguing: what if it's not the brightness of the galaxies that's wrong, but our estimate of their distance, based on their redness and our current model of cosmic expansion? "One of the most extreme possibilities is that the universe was expanding faster shortly after the Big Bang than we predict," says Boylan-Kolchin, "which might require new forces and particles." So could there be something wrong with our understanding of the behaviour of space itself in the early universe? While this is only one possible solution to the curious Webb observations, some theoretical cosmologists working at the other end of the Big Bang story have recently been wondering the same thing.

A longstanding problem with the traditional Big Bang theory is the idea that in its first moment, the universe was a singularity – a single, infinitely dense point instant in space and time, out of which everything emerged. Singularities are points at which the mathematics of general relativity, which describe the relations between space, time and matter, break down completely. "The modern interpretation of singularities in

GROWING GALAXIES

Studies of individual galaxy collisions and computer simulations based on the Lambda-CDM model both suggest that galaxies grow in size and complexity through repeated collisions and mergers. As a result, astronomers expect to only find small, faint galaxies in the early universe.



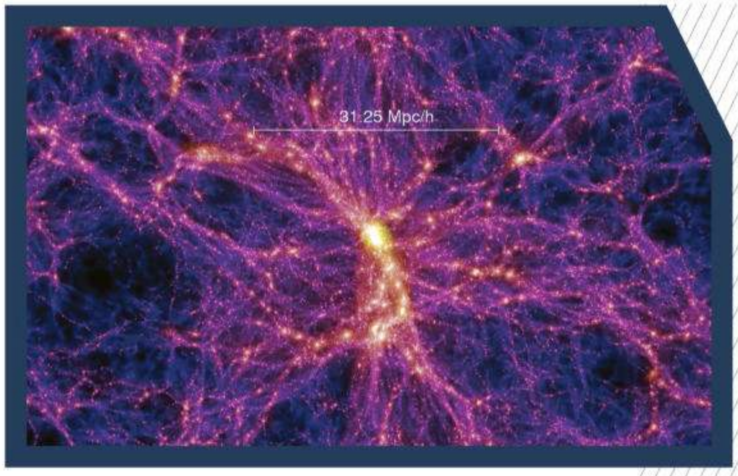


general relativity is that they represent a break-down of the theory, and therefore they need to be avoided," says Dr Marco Bruni of the University of Portsmouth's Institute of Cosmology and Gravitation.

One possible way around this problem preoccupied Stephen Hawking in the later decades of his career, and is the subject of a new book, *On the Origin of Time*, by his long-time collaborator Professor Thomas Hertog. Hawking and Hertog concluded that, due to its tiny scale, the early universe can only be understood through the equations of quantum physics. This would make the first moments of the universe inherently unpredictable, but might also cause space and time to 'blend together' – if you could wind the clock back, you would find time itself becoming increasingly spacelike and running ever more slowly, until the universe became static and timeless without ever quite reaching the point of singularity.

Along with graduate student Molly Burkmar, however, Bruni has been investigating another intriguing possibility. "We instead replace the singularity with a bounce within general relativity, using the negative pressure of dark energy and the positive curvature of space," they explain. Bruni and Burkmar's study was inspired in part by the similarities between inflation – a phenomenon that drove violent expansion very shortly after the Big Bang – and the dark energy that, after apparently remaining dormant, has caused the expansion of the universe to speed up once again in the past 5 billion years. Inflation is a core element of the modern Big Bang theory – an event in which one small fragment of the infant universe blew up to enormous size, magnifying tiny quantum fluctuations within it until they were large enough to become the seeds of large-scale structure in the later universe, before coming to an end just as suddenly as it began.

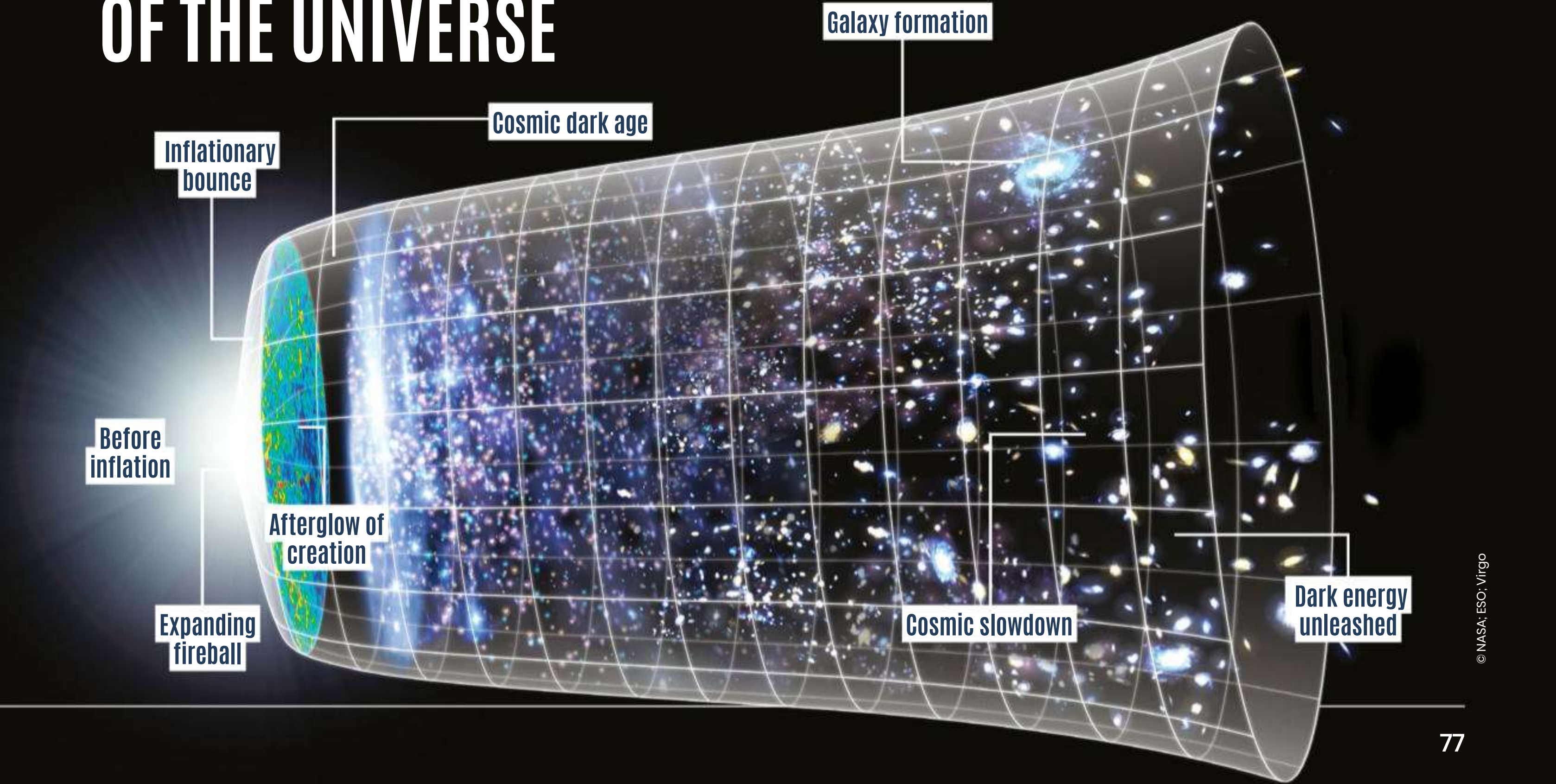
"Dark energy causes the expansion of our universe to accelerate," Burkmar and Bruni say. "It has negative pressure, and therefore can make gravity repulsive, rather than attractive. In general, anything that has a negative enough pressure plays the role of a dark energy, and can evolve with time. The



A A simulation shows visible matter (yellow) being drawn by gravity towards concentrations of dark matter seeded in the early universe.

B Temperature differences in the cosmic microwave background radiation are the result of tiny density variations in the primordial universe, magnified by inflation.

A BRIEF HISTORY OF THE UNIVERSE



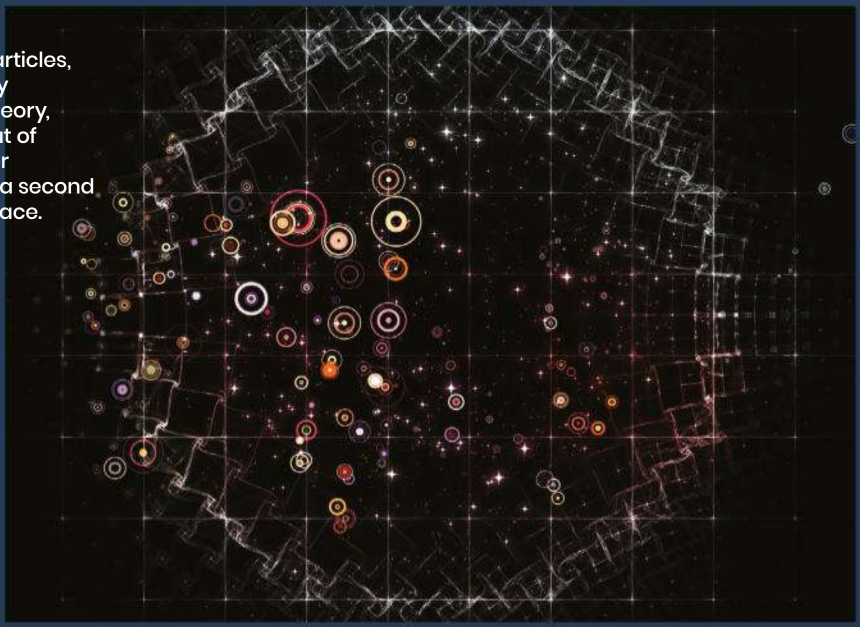
WHAT CAUSED THE BIRTH OF THE UNIVERSE?

Many scenarios illustrate how our universe may have come into being

There was nothing

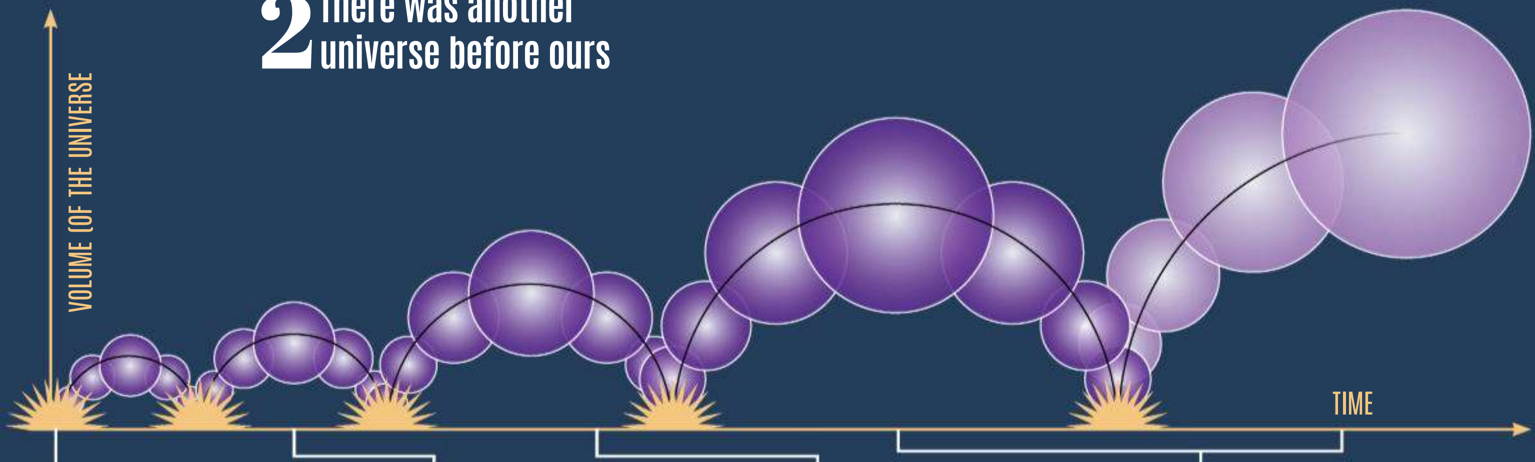
1 Strictly speaking, no scientist believes that our universe started from literally nothing. There always has to be something to cause another action to occur. However, many cosmologists are not yet convinced that there was anything before the Big Bang. Lawrence Krauss is one such scientist and he's developed a theory of 'quantum nothingness' from which the universe could have originated.

The theory involves so-called 'virtual particles', which flit in and out of existence for fractions of a second in empty space. They are predicted by quantum theory and their effects can be observed. Krauss says that if you remove virtual particles from a region of space it still has an energy density – but it shouldn't. It's from this form of 'nothing' that our universe could've started.



Virtual particles, predicted by quantum theory, flit in and out of existence for fractions of a second in empty space.

2 There was another universe before ours



Big Bang and expansion

In the cyclic model, a universe may have a true origin as normal and go through an inflation and expansion phase.

Everything now stalls

In a cyclic universe the cosmos may expand to a point and then stall. This may happen from the gravitational effect of matter.

Universe in reverse

Gravity takes over and the universe now contracts, with galaxies moving towards one another instead of further away.

Big bounce and next phase

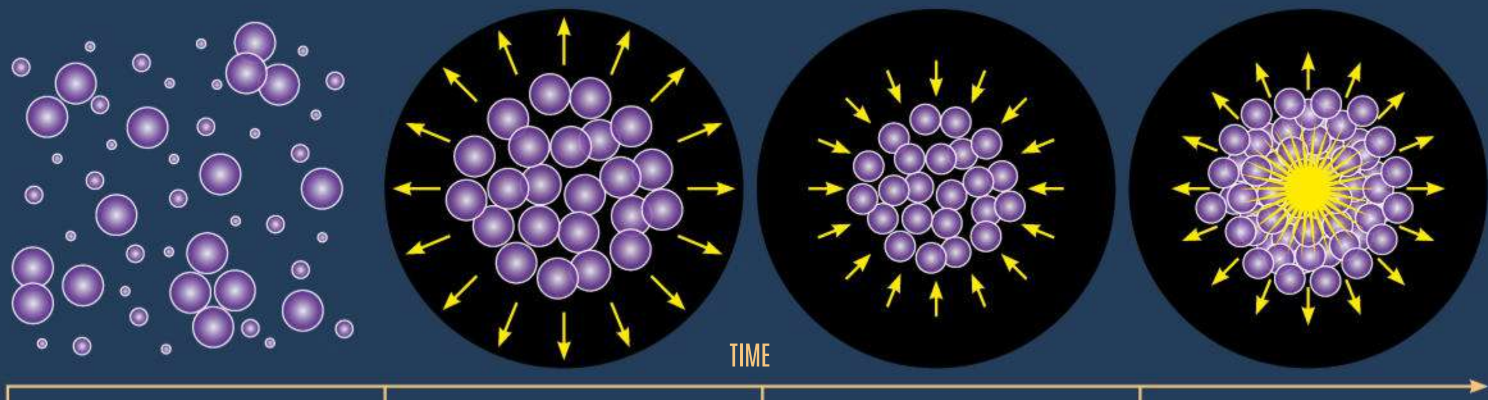
Inevitably, the universe can only contract so far. A 'big bounce' initiates the next expansion phase. The process continues.

similarity between inflation and the current dark-energy-dominated period is that the expansion of the universe is accelerating in both cases."

Inspired by this similarity, the cosmologists set out to look at how the universe might evolve in a situation where the pressure from dark energy could change dramatically at different points in cosmic evolution. "Our research involved analysing the consequences of Einstein's [general relativity] equations in the presence of a dark energy that can evolve between a maximum and a minimum value," they explain. "During the contraction of the universe, the dark energy increases… so the size of the universe reaches its minimum and bounces. Then the universe expands, and the dark energy decreases towards its minimum. When the dark energy is close to its maximum or minimum, the universe accelerates [growing or shrinking rapidly]. Therefore, in our model, this dark energy explains both the bounce [of inflation], and the observed accelerated expansion today."

Bruni and Burkmar's work stands in contrast to other models that treat inflation as a separate phenomenon from dark energy and require space to have new exotic

3 It's always been there



An empty infinite universe
In this scenario, the universe has existed forever and was nearly empty for that time. Then gravity took over and matter started to clump together.

Expanding internal region
The density of matter is such in some regions that it forms an incredibly massive black hole, the internal region of which experiences an expansion.

A big crunch
Inside the huge black hole, matter again collapses under the intense gravity and increases in density up to a limit imposed by physics.

The Big Bang
When it can't stand any more, quantum fluctuations cause the matter to expand outwards in a typical Big Bang scenario within its black hole universe.

It is one universe of many

4 Eternal inflation theory was proposed in 1983 by physicist Paul Steinhardt as an extension of the cosmic inflation and Big Bang theories. Alan Guth, Andrei Linde and Steinhardt originally developed cosmic inflation theory to explain some problems with the Big Bang model, and it involved an exponential but rapid expansion of our universe.

The cause of cosmic inflation still remains somewhat vague, but for eternal inflation, Guth proposed in 2007 the existence of a 'false vacuum' or region of space with a positive energy density – similar to expanding bubbles forming in a boiling liquid. In this manner, certain regions of space-time (or 'universes') would be affected by their own form of cosmic inflation, before the positive vacuum moved on to another region.

As of yet, this scenario lacks evidence, but if true, then our universe could exist as a nodule on another universe as part of a 'multiverse'.

properties in order to explain how it was triggered and why it went away. What's more, if inflation did not mark a beginning but a 'bounce', it opens up the possibility that our universe is just the latest iteration in a potentially infinite series extending to the past and future. Today's cosmos emerged from a previous bounce, and one day the changing influence of dark energy will reverse its current expansion, drawing everything back to another bounce in the far future. It's an intriguing idea – though there's one important limitation; in order for the bounce to work, space itself has to have that 'positive curvature' that Bruni and Burkmar discuss. That is, there must be enough mass and energy within the universe to eventually bring the contraction to a halt – something that is far from certain.

But what would conditions within the 'bounce' itself be like? Bruni and Burkmar emphasise that it still has to take place at a point where the universe is extremely compact and very, very hot: "[It] necessarily has to occur at a high enough energy that all the standard physical processes that

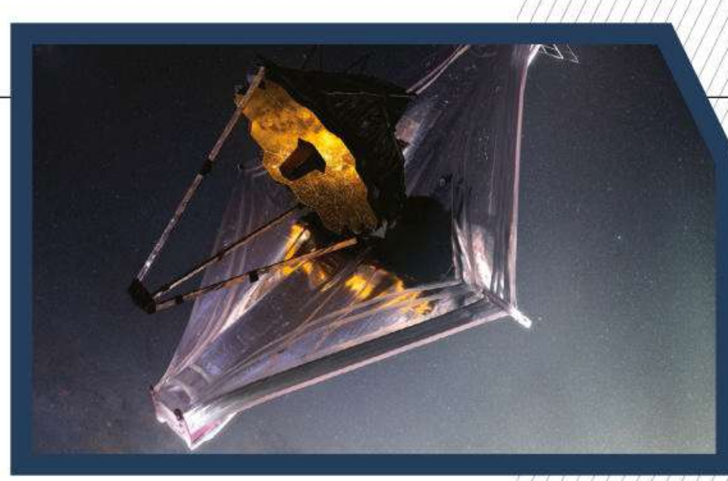
A Another theory suggests that our universe is one of many that exist parallel to one another and is part of a multiverse.

take place in the cosmic evolution can happen," they elaborate. "The observed abundances of light elements in the universe are well explained by so-called 'big-bang nucleosynthesis', but this doesn't need a singularity – just a 'big bang' in the sense of a very high energy state where matter is hot enough for fusion of protons and neutrons into lithium, helium and so on. As for inflation, the proof in the pudding would be to work out if the accelerated phase around the bounce is long enough to produce the initial seeds for the formation of structures in the universe. This probably means that the bounce has to occur at really extreme energies."

If the universe does indeed contract back to a superdense, superhot 'big crunch' before each bounce, then it would erase almost every trace of its previous iteration, as matter disintegrated and transformed back into pure energy in accordance with Einstein's famous equation E=mc^2. Indeed, the pair's calculations suggest that allowing matter or even radiation to persist during the period of reversal 'spoils' the bounce – everything must become dark energy. One thing that might survive, however, are black holes from the previous universe.

Although this 'bouncing' universe model offers a clever explanation for inflation by tying it to today's dark energy, Bruni emphasises that it doesn't attempt to explain the origin of the universe. "Inflation doesn't provide a solution for the beginning – but it leaves open the question of what happened before." It's likely to remain just that unless the pair can find concrete predictions that will allow it to be proved or disproved through observation. "The smoking gun for a bounce period could come from predicting the gravitational waves that should be produced after the bounce: these waves [telltale distortions in spacetime caused by superdense, rapidly changing objects] should be different from those produced during traditional Inflation. It would then be for future gravitational wave experiments to test the different possible bouncing models."

Giles Sparrow
Space science writer
The author of over 20 books, Giles holds a degree in astronomy and is an editor specialising in science and technology.



A Every aspect of the Webb, from its mirror and instruments to its sunshield and orbit, is designed to capture faint infrared radiation from the most distant and ancient galaxies.

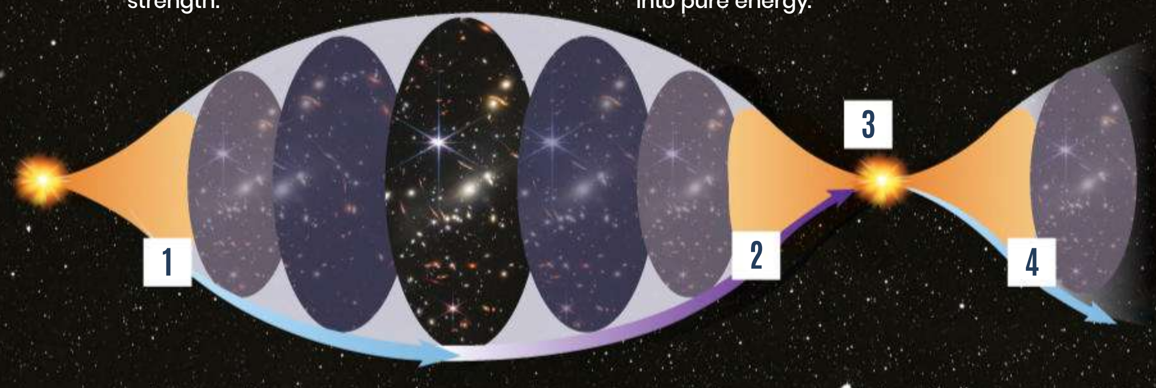
ARE WE IN A 'BOUNCING UNIVERSE'?

1 Inflation
Very early in the current universe, something drove the rapid expansion called inflation. The bouncing universe theory suggests this was the pressure of dark energy, which later diminished in strength.

2 Contracting universe
According to the theory, the strength and direction of dark energy can oscillate; in the far future, it could effectively reverse, causing space to contract.

3 Big Crunch
As the future universe grows smaller, the strength of dark energy increases rapidly. The universe becomes hot and dense once again, and matter is transformed back into pure energy.

4 A fresh start
Before space collapses to a singularity, the effect of dark energy reverses and drives a new burst of inflation – the universe is reborn.



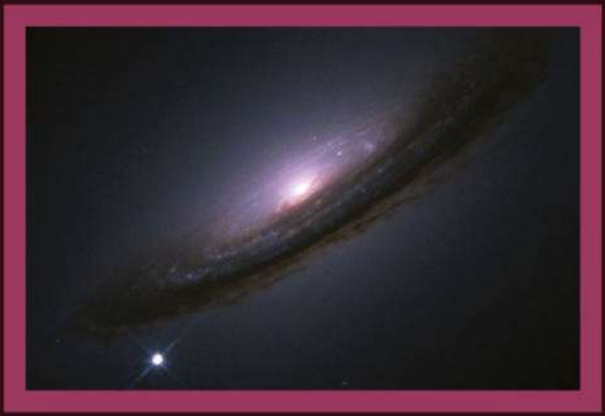
WHEN STARS GO SUPERNOVA

THE TITANIC ERUPTIONS THAT GIVE RISE TO LIFE

OUR STELLAR NEIGHBOURS DUE TO EXPLODE

"NO ONE KNOWS WHAT THIS EXPLOSION IS"

Astrophysicist Christopher Frohmaier



A Type Ia supernova shining as brightly as the centre of the galaxy it's in

Place your fingers on your wrist and check your pulse. You can feel the blood pumping around your body, delivering oxygen from your head to your toes. That oxygen is ferried around by trillions of red blood cells, each just 0.008 millimetres across. The element iron plays an indispensable role in this oxygen delivery, but the universe would contain very little iron if it weren't for a ferocious type of exploding dying star called a supernova. Without supernovae, you simply wouldn't exist.

We often think of the Sun as the quintessential star, but it's not massive enough to go supernova when it dies. According to Dr Christopher Frohmaier, a supernova researcher at the University of Southampton, to detonate in this most spectacular of celestial firework displays, a star needs a starting mass equivalent to at least eight Suns. The path that these massive stars follow towards their eventual demise as a supernova is inevitable. It's triggered by a fundamental shift in the interplay between the outward pressure generated by the nuclear fusion reactions in the star's core and gravity. "Throughout a massive star's life, it's in a constant balance between these forces," says Frohmaier.

Things begin to change when the hydrogen that sustains the nuclear reactions runs out. "The star will burn sequentially heavier and heavier elements to support its outer layers," Frohmaier says. Nested shells of helium, carbon, oxygen, neon, magnesium and silicon build up as the star exhausts its supply of successive elements and desperately scrambles for something new to burn. Eventually, the star's nuclear reactions produce iron from the silicon, which builds up the middle of the core. "The phase of converting silicon to iron can be over in a matter of hours," Frohmaier says. That compares to perhaps billions of years burning hydrogen into helium.

It's at this point that the nuclear reactions switch off. Iron is the most stable element in the periodic table – burning iron requires more energy to go in than comes out, and so it simply doesn't happen. Now unsupported, the star's outer layers come crashing down, building up an intense pressure on the core that breaks the iron back down into helium. "It's called photodisintegration," Frohmaier says. "And it also creates an overwhelmingly large number of neutrinos."

Neutrinos are tiny, almost-massless subatomic particles. The photodisintegration of the iron core creates approximately 10 billion trillion trillion trillion trillion neutrinos. "The neutrinos are blown outwards and drive the supernova explosion by pushing against the star's outer layers," Frohmaier explains. It's a slightly surreal role for neutrinos to play, as they are famously very antisocial particles. You would need a light year of lead to have a 50:50 chance of halting a single neutrino, yet there are so many produced by photodisintegration that their collective power blasts an entire massive star apart. In a short ten-second salvo, the neutrinos release almost a quadrillion quadrillion quadrillion Joules of energy. That's about the same amount of energy as the Sun will release in its entire 10-billion-year lifetime.

Astronomers call supernovae like these core-collapse supernovae. However, despite the huge amount of energy they release, when astronomers spot a core-collapse supernova in the night sky, they aren't observing the light from the explosion itself. "What we are seeing is radioactive decay," Frohmaier says. The supernova produces vast amounts of a rare form of the element nickel, known as nickel-56. It's unstable, and so breaks down - or decays - into cobalt and iron. This process creates a lot of gamma rays – the most energetic form of light. "All the material thrown out from the explosion gets energised by those gamma rays," says Frohmaier. That material then glows with visible light, which is what lights up the night sky and alerts astronomers to the death of a massive star.

And that light can be searingly bright. In 1054, Chinese astronomers wrote about a 'guest star' that suddenly appeared in the sky. It was so bright that it could be seen during the day for a month and took almost two years to fade from the night sky. Today we know that they witnessed a supernova explosion, the remnants of which form the Crab Nebula (Messier 1) in the constellation of Taurus, the Bull. Betelgeuse, not too far away in the constellation of Orion, will do something similar in the future. Astronomers can get deeper insights into the mechanics of supernovae by breaking up their light into spectra, much like how a raindrop splits sunlight to create a rainbow. Hidden within this stellar spectrum are so-called absorption features that point to the presence of various elements within the debris from the supernova. All supernovae with hydrogen in their spectra are classed as Type II supernovae.

There's a separate class of supernovae, known as Type I, that don't have hydrogen in their spectra. For Type Ib, that's because fierce winds blew the hydrogen outwards from the star before it collapsed. For Type Ic the star also blew its helium away, meaning there's no hydrogen or helium present in the spectrum. These are still core-collapse supernovae, though. But by far the most famous Type I supernova – known as Type Ia – has a completely different origin. "No one knows exactly what the explosion mechanism is," Frohmaier says, although all options point towards another remnant of dead stars: white dwarfs.

Stars that start off less massive than eight Suns aren't big enough to trigger core-collapse supernovae. These stars move from burning hydrogen to burning helium, eventually fashioning a core of carbon and oxygen about the same size as Earth… a white dwarf. There isn't sufficient pressure to fuse carbon, so why doesn't a white dwarf collapse? "White dwarfs aren't supported by fusion, but by something called degeneracy pressure," Frohmaier says. There's a rule in quantum physics that says it's impossible to force certain particles into the same state, so try as it might to collapse, a white dwarf cannot.

There's a limit to how massive a white dwarf can be, however. "If you exert too much pressure then the temperature will rapidly increase and the carbon will undergo thermonuclear runaway," Frohmaier says. In other words, it detonates like a nuclear bomb and explodes outwards as a Type Ia supernova. This mass threshold is known as the Chandrasekhar limit after the Indian astrophysicist Subrahmanyan Chandrasekhar, who calculated it aged just 19 during a sea voyage to Europe in 1930. It's possible for a stable white dwarf to approach this threshold by gaining mass from somewhere else.

Frohmaier says there are two main options being considered by astrophysicists. The first, called the single-degenerate scenario, involves the white dwarf ripping gas from a companion star. This could be an ordinary star like the Sun, or a Sun-

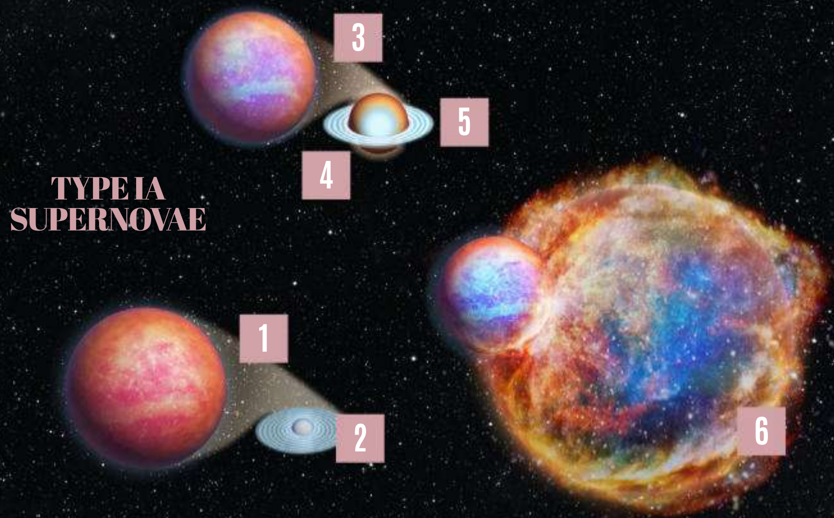
A The star Wolf-Rayet 124 is giving hints that it's due to explode soon

SN 1987A

Supernovae are reasonably common - about two explode every century in a galaxy like our Milky Way. With hundreds of billions of galaxies to observe, astronomers see them on a regular basis. Usually, they're far away, meaning astronomers can struggle to see them in detail. Astronomers were handed an astronomical gift in 1987 when a Type II supernova exploded in the Large Magellanic Cloud, one of the satellite galaxies of the Milky Way. At just 168,000 light years away, they could observe never-before-seen features of the explosion. It was the first time that astronomers were able to confirm that radioactive decay is responsible for the visible light we see from core-collapse supernovae, for example. SN 1987A was also pivotal in our understanding of the role that neutrinos play. Several hours before the visible light from the supernova arrived on Earth, three separate neutrino observatories pinged with neutrino detections. It confirmed predictions from theoretical models that 99 per cent of the energy of a supernova is carried away by these ghost-like subatomic particles.

HOW DO STARS DETONATE?

Stunning supernova explosions can come from very different stellar systems



1 Finding the right stars

These supernovae occur when a white dwarf is found in a binary pair with another star.

2 Matter transfer

Two stars orbit close enough to each other that matter will transfer from the companion onto a white dwarf star in a process called accretion.

3 Squeezing down

This accretion of matter from its companion adds extra mass. The additional gravitational forces compress the already highly pressurised core of the white dwarf.

4 A star reborn

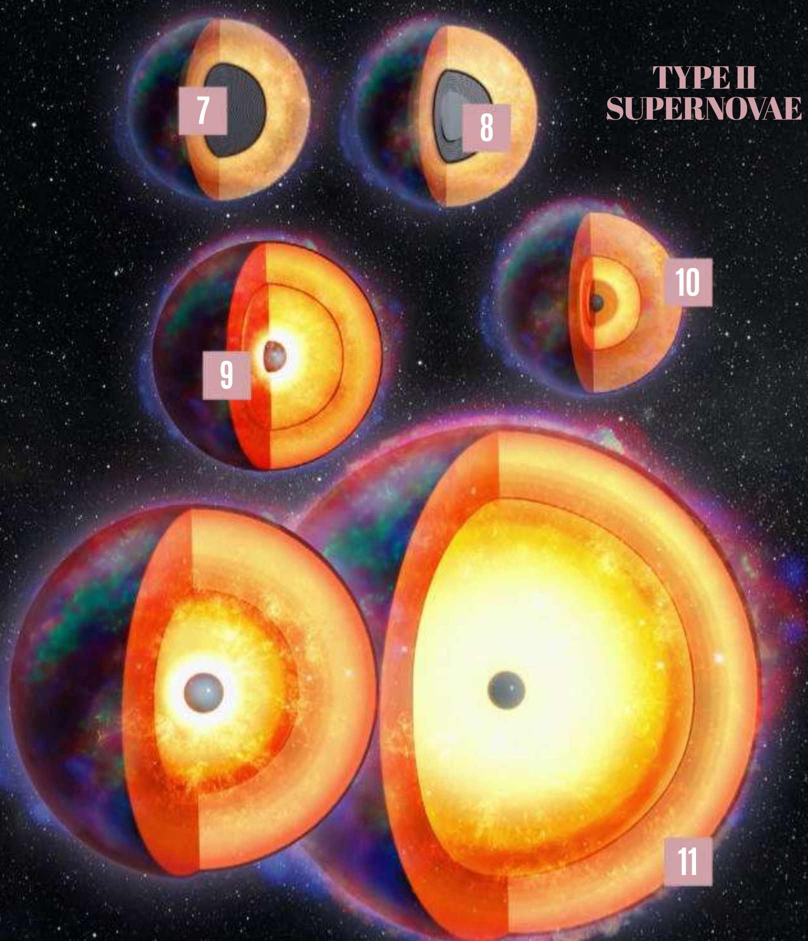
As the star approaches the Chandrasekhar limit, the dying star comes to life again and undergoes fusion in its centre.

5 Limited gains

However, white dwarfs can only get so massive through accretion. The Chandrasekhar limit puts their maximum size at about 1.4 times the mass of our Sun.

6 Outward pressure

This time the star cannot expand to accommodate the outward pressure. Instead, expansive forces build up.



7 Out of gas

Supergiants like Betelgeuse will eventually run out of hydrogen and helium fuel, the nuclear burning of which prevents them collapsing in on themselves.

8 Elemental onion

Gradually, heavier elements build up at the star's centre, which becomes layered like an onion, with lighter elements towards the outside of the star.

9 Burning fuels

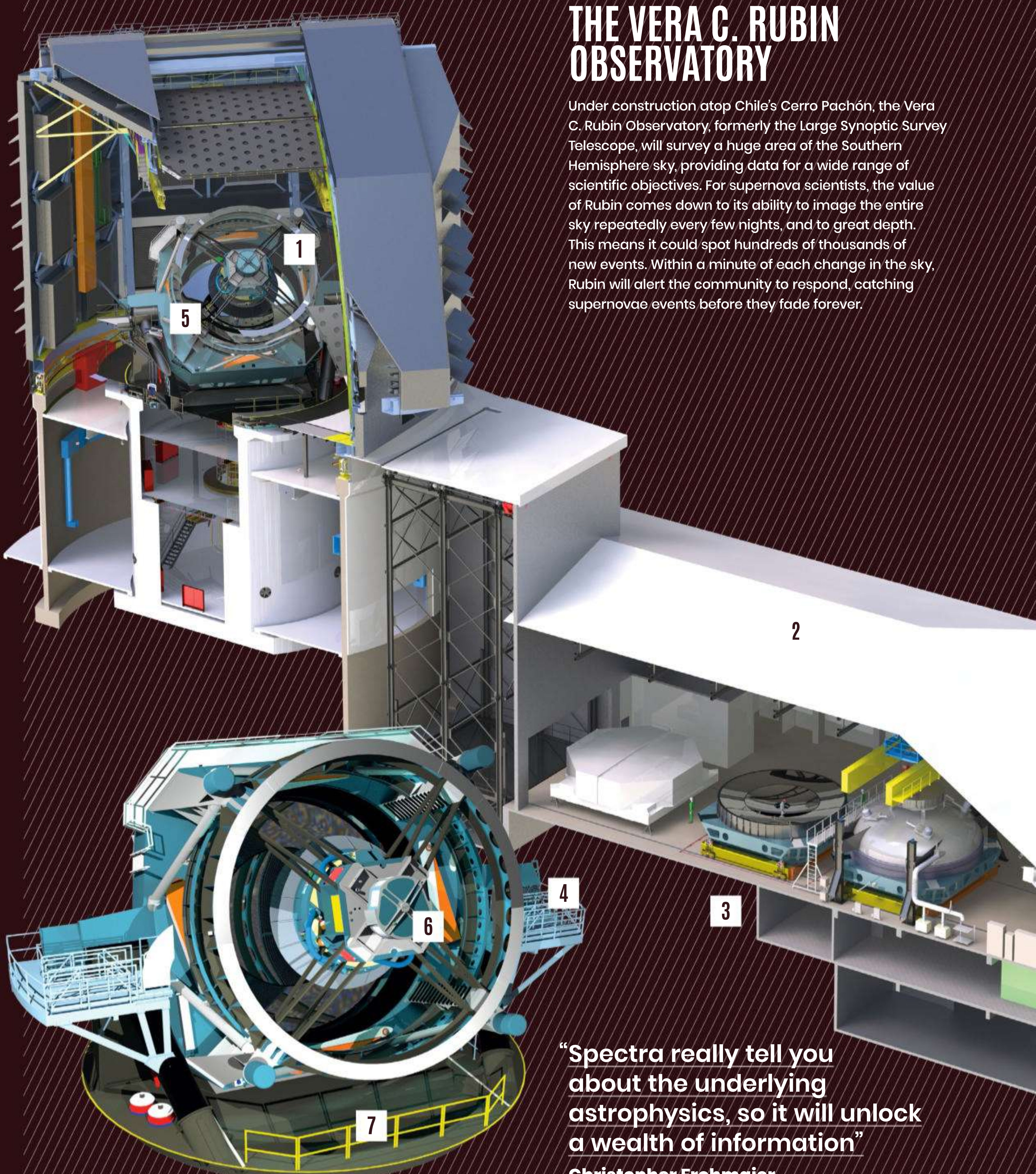
For stars this size, their mass and compressional forces at the core allow them to fuse heavier elements to maintain the outward pressure that fights gravity.

10 Resistance is futile

This act of resistance holds until the star's innermost core is composed of iron, which refuses to fuse. Gravity finally wins out, and the star's outer layers collapse inwards.

11 Shock wave rebound

This inward implosion bounces back off the core as a rebounding shock wave that blows the whole atmospheric envelope off the star, creating the spectacular supernova.



THE VERA C. RUBIN OBSERVATORY

Under construction atop Chile's Cerro Pachón, the Vera C. Rubin Observatory, formerly the Large Synoptic Survey Telescope, will survey a huge area of the Southern Hemisphere sky, providing data for a wide range of scientific objectives. For supernova scientists, the value of Rubin comes down to its ability to image the entire sky repeatedly every few nights, and to great depth. This means it could spot hundreds of thousands of new events. Within a minute of each change in the sky, Rubin will alert the community to respond, catching supernovae events before they fade forever.

"Spectra really tell you about the underlying astrophysics, so it will unlock a wealth of information"

Christopher Frohmaier

1 Large mirror Rubin's reflecting telescope contains an 8.4-metre (28-foot) primary mirror that can track across at sufficient pace to image the entire sky every few nights.

2 Environment The design of the observatory takes advantage of the mountain's natural topography. Its orientation was selected after extensive weather testing.

3 Keeping cool To protect the mirror, the heated operation spaces are located below the service level. The heat-generating equipment is below that, farthest from the telescope.

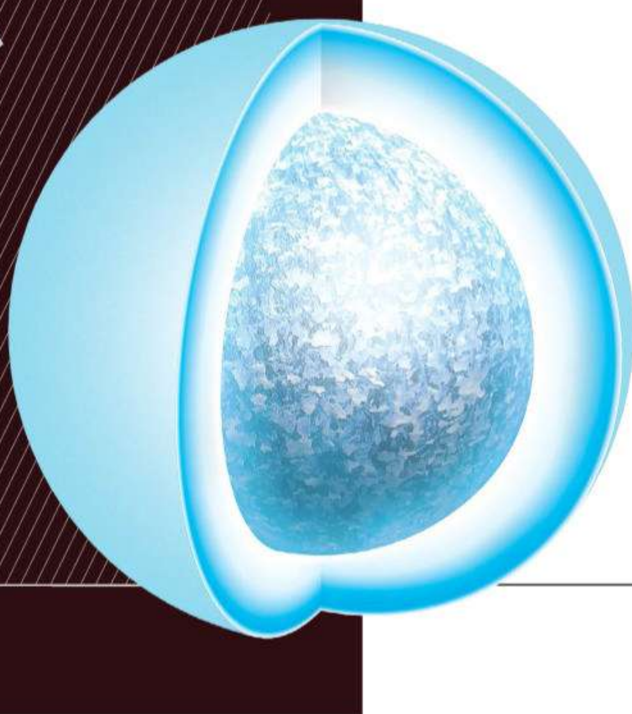
4 Wide-angle lens To maximise its potential to spot new transient phenomena, Rubin has a 3.5-degree field of view – the Sun as seen from Earth is only 0.5 degrees across.

5 Multi-band Rubin will carry out a deep ten-year imaging survey in six broad optical bands to maximise the data provided on any supernovae or progenitors imaged.

6 On-site maintenance The observatory has its own dedicated cleaning and coating area where the mirrors are washed and recoated during operations.

7 Big camera Images will be recorded by a 3.2-gigapixel camera. It will take a 15-second exposure every 20 seconds to help detect new high-energy events.

▲ The lens of the camera that will conduct the LSST



▼ About the size of Earth, a white dwarf is made of carbon and oxygen

like star that's itself on the way out, having puffed up into a so-called red giant. However, the ensuing supernova would interact with some of the hydrogen of the companion star, causing it to glow. "No one has seen that hydrogen," says Frohmaier, which means that most researchers are starting to favour the so-called double-degenerate scenario instead. Picture two Sun-like stars orbiting one another in a binary system. Such a scenario is very common, as at least half of the stars in the universe are thought to exist in these binary pairs. Both stars reach the end of their lives and become white dwarfs. The two white dwarfs circle around one another, gradually spiralling inwards towards oblivion. "They collide into a single white dwarf that's too massive to exist," Frohmaier says, and in a matter of milliseconds they detonate as a Type Ia supernova.

Understanding what causes these enigmatic explosions is vital because Type I supernovae are used as cosmic rulers to measure distances in the universe. If every Type Ia supernova is the result of a detonation of a white dwarf, or dwarfs, with a total mass close to the Chandrasekhar limit, then each explosion will have a similar brightness, thus those that appear dimmer to us must be further away. In the late 1990s, astronomers used measurements of Type Ia supernovae to show that the expansion of the universe appears to be speeding up. If it continues to accelerate as it is, then all structures in the universe will be torn apart in around 22 billion years in an event astronomers call the 'Big Rip'. Exactly what's driving the quickening expansion is unclear, but cosmologists point to the influence of a mysterious entity dubbed dark energy – yet they don't know what it is or how it works. Understanding Type Ia supernovae better might provide valuable clues.

Astronomers refer to objects like Type I supernovae that have an inherently fixed brightness and can be used to measure cosmic distances as standard candles. Frohmaier prefers to call Type Ia supernovae 'standardisable candles'. "There's some variation in

the brightness of these objects," he says. Astronomers have to make corrections for these subtle differences in order to use them as celestial rulers. "That's worked well for 20 years, but as we enter the next era of telescopes we're being held back by our lack of understanding of astrophysics."

Astronomers may not have to wait much longer for answers. Construction is almost finished on the much anticipated Vera C. Rubin Observatory in Chile, which should see the start of full operation towards the end of 2024. It's home to the largest digital camera ever constructed, with a total of 3,200 megapixels, and it's about the size of a person. This colossal camera will be at the heart of an observing run known as the Legacy Survey of Space and Time (LSST). Astronomers expect to spot hundreds of thousands of new supernovae. "It will be revolutionary for cosmology," Frohmaier says.

While this will spot supernovae, it won't be able to measure their spectra. For that astronomers will turn to another facility in Chile. The 4-metre Multi-Object Spectrograph Telescope (4MOST) is an instrument attached to the Visible and Infrared Survey Telescope for Astronomy (VISTA) at Paranal Observatory. Rather than measuring the spectrum of one supernova at a time, 4MOST will be able to observe the spectra of 2,400 supernovae simultaneously. "Spectra really tell you about the underlying astrophysics, so it will unlock a wealth of information," says Frohmaier, who was recently announced as the project's deputy project scientist. It will allow astronomers to compare models of supernova explosions built in supercomputers to real data to check if they've built a realistic model.

Perhaps astronomers will finally be able to tease apart the mysteries that surround Type Ia supernova, not only measuring distances in space more accurately, but also getting a clearer understanding of why our universe continues to expand at an ever quickening pace.

A supernova would have a devastating impact on planets and its wider solar system

Colin Stuart
Astronomer and space science writer
Colin holds a degree in astrophysics, has written over 17 books on space and has an asteroid named in his honour.

FIVE STARS READY TO EXPLODE

Betelgeuse

Stellar evolution models suggest it should go supernova anytime in the next 100,000 years, when it will be as bright as the full Moon in the night sky. Even before its recent dimming, Betelgeuse showed the most variation of any progenitors.

Antares

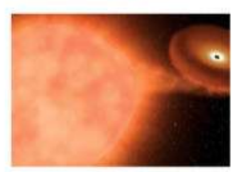
The red eye of the scorpion in the constellation of Scorpius is due to go supernova in the next million years. With a mass 15 to 18 times that of our Sun, it will be spectacular, though its lack of variability suggests it's not quite ready yet.

Mu Cephei

Known as 'Herschel's Garnet Star', it's further away than Betelgeuse, but double its diameter, and therefore perhaps closer to death. Its supernova would likely produce a black hole while providing a 'guest star' as bright as Venus.

Eta Carinae

Observers have already seen this binary star throw out its outermost layers in a series of pulses. Much further away than Betelgeuse, its impending death could produce a gamma-ray burst or a superluminous supernova, easily visible from Earth.



V Sagittae

Made up of an ordinary star spiralling in towards a white dwarf, researchers have predicted a date later in this century for a supernova event that will create a 'new star' as bright as Sirius in the night sky.

FOCUS ON

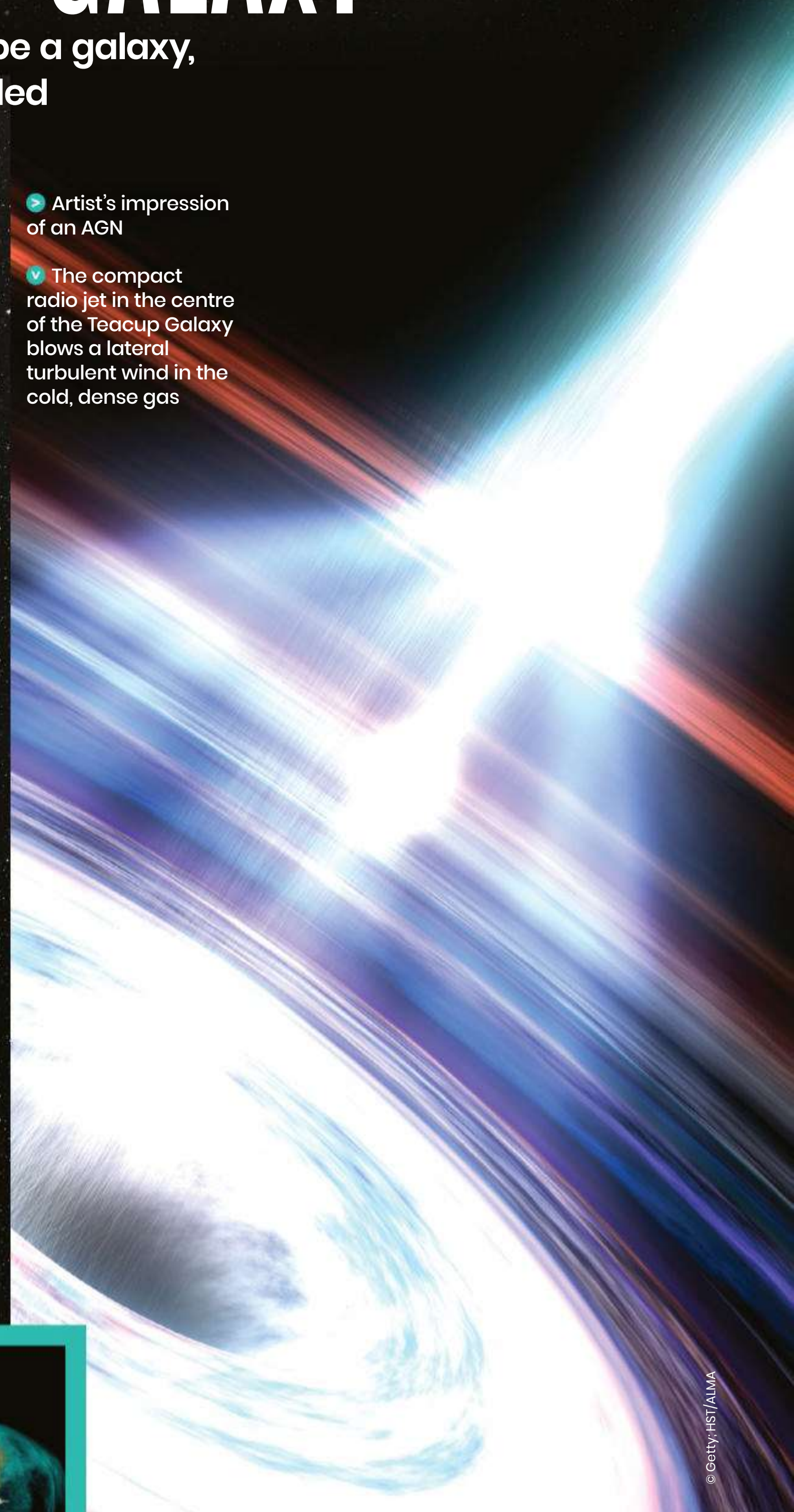
RELATIVISTIC JETS BUBBLING IN THE TEACUP GALAXY

Even low-power jets can help shape a galaxy, it just depends where they're headed

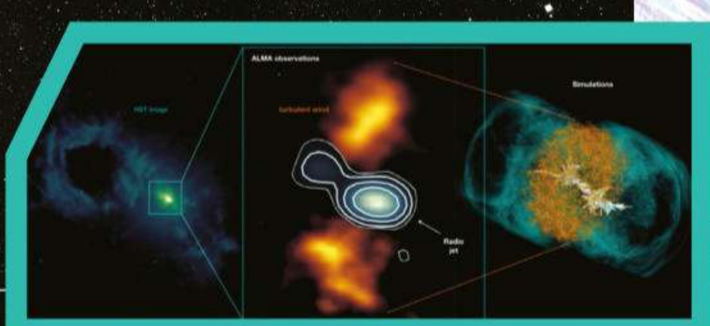
Reported by Briley Lewis

New research investigates how relativistic jets from a supermassive black hole have been shaping the Teacup Galaxy, giving it its iconic handle. Active galactic nuclei (AGN) are some of the most intense places in the universe, where supermassive black holes are gobbling up matter and spewing out jets that move at almost the speed of light. Astrophysicists know that these relativistic jets shape the galaxies they're in, stirring up and pushing out material as they shoot out from the central black hole. But not all jets are created equal – some are stronger and drastically change their surroundings by heating up the gas in their galaxies, stunting the galaxies' growth. Others are weaker, referred to as radio-quiet, but computer simulations suggest that they still have shockingly large effects and an ability to push around nearby gas. "It was previously believed that low-power jets had a negligible impact on the galaxy," said Christina Ramos Almeida, an astronomer at the Instituto de Astrofísica de Canarias (IAC) and co-researcher of the new study.

The team's new observations from the Atacama Large Millimeter/submillimeter Array (ALMA) show that at least in the Teacup Galaxy – a radio-quiet galaxy named for its appearance that lies about 1.3 billion light years from Earth – jets are moving, heating and accelerating the galaxy's gas. "Even in the case of radio-quiet galaxies, jets can redistribute and disrupt the surrounding gas, and this will have an impact on the galaxy's ability to form new stars," Almeida said. Much to the team's surprise, the biggest effects were actually perpendicular to the direction of the jets instead of head-on. "This is caused by the shocks induced by the jet-driven bubble, which heats up and blows the gas," said lead scientist and IAC astronomer Anelise Audibert. It turns out that even low-power jets have an impact – it just depends where they're headed.



Artist's impression of an AGN



The compact radio jet in the centre of the Teacup Galaxy blows a lateral turbulent wind in the cold, dense gas

© Getty; HST/ALMA

FOCUS ON

SUPERNOVA WRECKAGE BLASTS OUT COSMIC RAYS

Astronomers tracked cosmic rays to objects that launch particles with energy ten times greater than the Large Hadron Collider

Reported by Robert Lea

Some space radiation crashing into Earth has an explosive origin. Astronomers spotted wreckage from a supernova explosion potentially capable of blasting out high-energy particles – or cosmic rays – that frequently bombard Earth. Their new findings link shock waves and wreckage created by dying stars to natural high-energy proton accelerators in space, dubbed PeVatrons. These intriguing cosmic accelerators – which receive their name from their ability to boost the energies of particles to extreme petaelectronvolt (PeV) levels – have never been conclusively identified.

A handful of suspected PeVatrons were already fingerprinted before this study, including one at the centre of our Milky Way. The research team says their new find of a supernova explosion's leftovers – a cloud of material called G106.3+2.7 – could be the most promising candidate yet. The wreckage lurks 2,600 light years from Earth, possesses a comet shape and has a bright pulsar at one end. Because neutron stars form when stars undergo gravitational collapse, which also launches out supernovae, there's good reason for researchers to think the pulsar and the supernova cloud were created by the same violent event.

Using NASA's Fermi Gamma-ray Space Telescope, astronomers spotted a high-energy gamma-ray afterglow that implies G106.3+2.7 may be capable of blasting out particles at energies equivalent to a million billion electronvolts – ten times as great as generated by the Large Hadron Collider, Earth's most powerful particle accelerator. "Theorists think the highest energy cosmic-ray protons in the Milky Way reach a million billion electronvolts, or PeV energies," Ke Fang, assistant professor at the University of Wisconsin-Madison, said. "The precise nature of their sources, which we call PeVatrons, has been difficult to pin down."

Scientists suspect the supernova wreckage from dead stars accelerates particles to such high energies when charged particles are ensnared by magnetic fields around them. This process allows shock waves from the supernova to buffet the trapped particles repeatedly, increasing their energy each time. Finally, the particles are so energetic that the

> "Theorists think the highest energy cosmic-ray protons in the Milky Way reach a million billion electronvolts, or PeV energies" **Ke Fang**

supernova cannot hold onto them and the particles escape into space as cosmic rays.

Tracing cosmic rays back to supernova wreckage has been difficult because the protons that comprise cosmic rays are electrically charged, so cosmic rays are prone to scattering while interacting with magnetic fields as they journey through space. Astronomers can't easily tell from which direction the rays are coming when they finally reach our planet. But because the acceleration of protons to such high speeds causes the emission of gamma rays, this high-energy light could be a good proxy for detecting the source of cosmic rays.

Both Fermi and the Very Energetic Radiation Imaging Telescope Array System (VERITAS) detected gamma rays from inside the tail of G106.3+2.7. Other observatories have found extremely high-energy photons coming from the same area, indicating this could indeed be a PeVatron. "This object has been a source of considerable interest for a while now, but to crown it as a PeVatron we had to prove it's accelerating protons," researcher Henrike Fleischhack of NASA's Goddard Space Flight Center in Greenbelt, Maryland, said. "The catch is that electrons accelerated to a few hundred TeV can produce the same emission. Now, with the help of 12 years of Fermi data, we think we've made the case that G106.3+2.7 is indeed a PeVatron."

HOW DO STARS EXPLODE?

Stunning supernova explosions can come from very different stellar systems

1 Matter transfer
Two stars can orbit close enough to each other that matter will transfer from the companion onto a white dwarf star in a process called accretion.

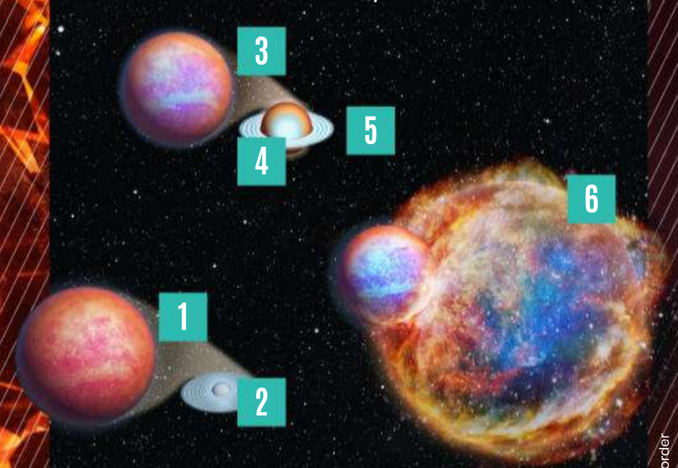
2 Finding the right stars
These occur when a white dwarf, like the one our Sun will leave behind after its death, is found in a binary pair with another star.

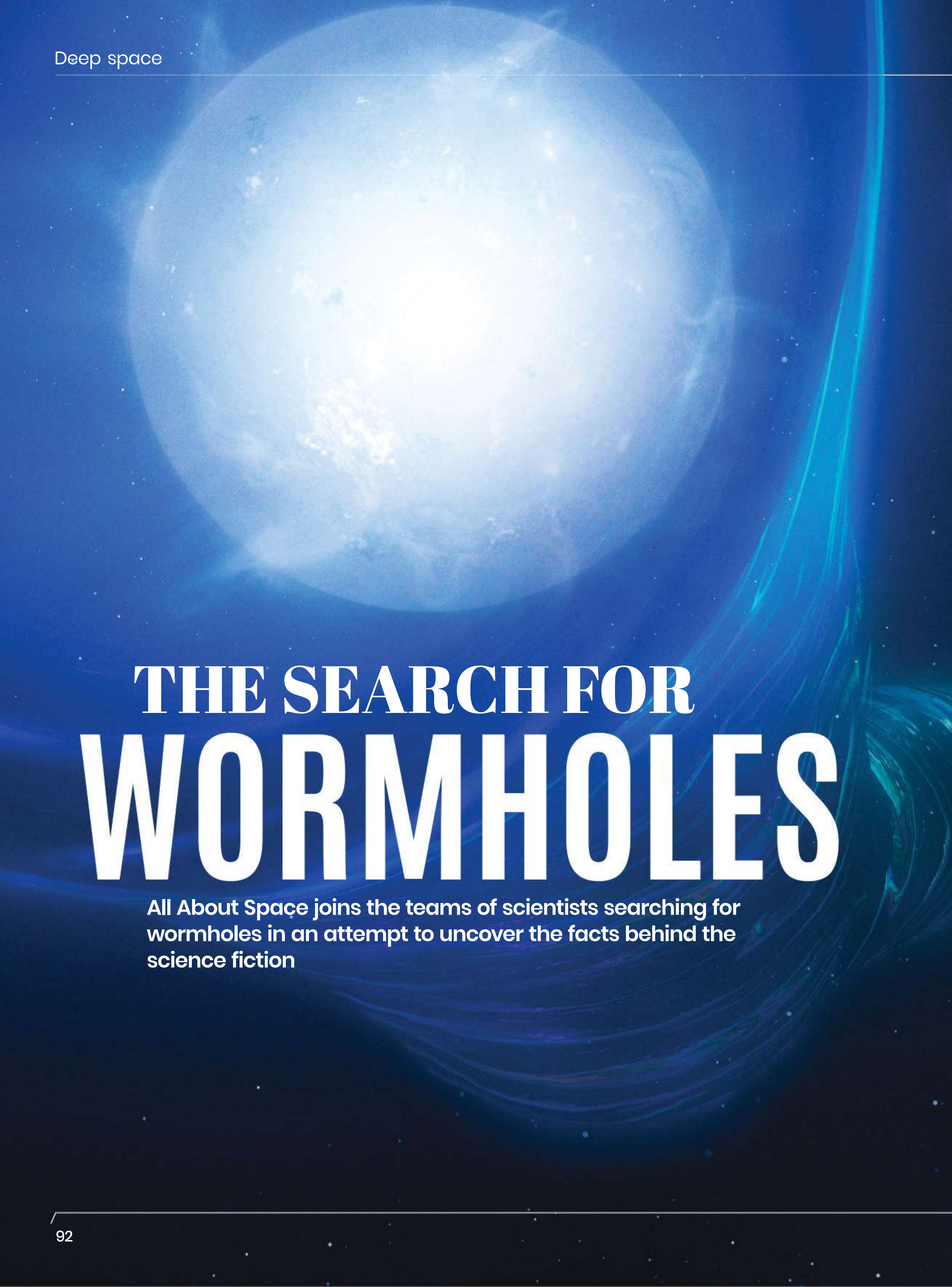
3 Squeezing down
This accretion of matter adds extra mass. The additional gravitational forces compress the already highly pressurised core of the white dwarf.

4 A star reborn
As the star approaches the Chandrasekhar limit, the dying star comes to life again and undergoes fusion in its centre.

5 Limited gains
White dwarfs can only get so massive through accretion. The Chandrasekhar limit puts their maximum size at about 1.4 times the mass of our Sun.

6 Outward pressure
This time the star cannot expand to accommodate the outward pressure of its newly kindled fusion burning. Instead expansive forces build, creating a violent supernova.





THE SEARCH FOR WORMHOLES

All About Space joins the teams of scientists searching for wormholes in an attempt to uncover the facts behind the science fiction

Wormholes are so-called gateways that provide a shortcut through the fabric of space-time. They can be thought of as tunnels with ends capped by an ever-hungry black and a white hole, the black hole's time-reversed cousin that prefers to spit things out if anything comes too close to its event horizon.

It's true that a wormhole never looks out of place in science fiction – for example, lurking in the universe of *Star Trek: Deep Space 9* and employed by captain Benjamin Sisko and his crew of the Defiant. They use the hole to travel from the Alpha to the Gamma quadrant on the other side of the galaxy at unprecedented speed – certainly a thrilling prospect.

However, we still don't know for sure whether traversable wormholes like the ones in *Star Trek* really exist. Even finding the slightest hint of these natural portals almost seems like a pipe dream. With this in mind, it would seem odd that massive organisations are still looking, such as Project RadioAstron, the Soviet Union's first radio astronomy research facility.

"The search for wormholes seems like a worthy undertaking," muses assistant professor of astrophysics Robert Owen of Oberlin College. His thoughts are echoed by Igor Novikov, a Russian theoretical astrophysicist and cosmologist who made an important contribution to the theory of time travel during the mid-1980s. The Novikov Self-consistency Principle states that it's impossible to make paradoxes of time. "There's a hypothesis that primordial wormholes exist and can connect some regions in our universe in the model of the multiverse," Novikov, who is based at the Russian Space Research Institute in Moscow, explains. "In this case, the search for astrophysical wormholes is a unique possibility to study the other universes."

These elusive tunnels through space wouldn't just be a major discovery in and of themselves, but could even open up avenues to bigger things – possibly even answering some of the deepest questions about the nature of our universe. Although we haven't found them yet, the laws and complex equations that underpin Einstein's theory of general relativity say that technically they should exist out there somewhere – maybe as microscopic structures the size of atoms, or giant but impassable wormholes connecting the black holes in the centres of galaxies. However, should a stable wormhole be found, it might be possible to travel down it and end up in another place, and another time, in the universe.

"There's a hypothesis that wormholes exist and can connect some regions in our universe"

Igor Novikov

Clearly, the practicalities of finding a wormhole is a challenging subject entirely on its own, and one that scientists like Owen relish. The search wouldn't merely mean searching for the wormholes themselves, but the equally elusive white holes that are supposedly tacked onto one end, making the task of locating them all the more difficult. However, Owen believes that even in light of the obvious difficulties, the hunt for wormholes must be supported. He studies the relativistic effects of black holes and neutron stars colliding to make gravitational waves – ripples in the curvature of space-time – to find traces of the holes.

So, is finding a wormhole really that important at all? **All About Space** asked theoretical physicist Kristan Jensen at the University of Victoria. Alongside Andreas Karch, a professor of physics at the University of Washington, Jensen looks at wormholes purely from a theoretical perspective. "Honestly, no," he initially answers. "I find it unlikely that there are wormholes [of notable size] in our universe." This is because he – as well as quite a few in the scientific community – believe that we might be hard-pressed to find these tunnels through space. Paradoxically, it seems that the theory suggesting that wormholes exist also makes an equally strong case for how they could never be real.

If you were to open up a wormhole, you might find it quickly begins to fall apart.

Egyptologist and linguist Daniel Jackson, the protagonist in *Stargate*, might have found himself cautiously stepping into a stable wormhole when he cracked the code behind the hieroglyphics that opened a pathway to another galaxy. The reason that we might not be able to find a wormhole could simply be that in reality they're incredibly unstable entities.

Owen suggests that you just need to think about travelling through one to get a full picture of why this is. "In general relativity, time travel is actually one of the things that naturally comes along with wormholes," he says. "However, the idea that wormholes could be used for travelling through time is usually taken as an indication that they probably couldn't exist." Owen references several calculations that have been processed, showing that wormholes naturally destroy themselves before they could even offer us the chance to be used to travel back in time. "Imagine that I had a wormhole with both throats [in other words, both openings to the wormhole], in my office and I could step into one of them and emerge from the other ten seconds earlier," he describes. "For those ten seconds there would actually be two of me in the office. But what if I then chose to wait those ten seconds and then step through [the black hole again], simultaneously with my earlier self?" The answer is that Owen and his past self would again emerge from the white hole ten seconds earlier and there would now be three of him. "If I did it again, there would be four of me, five, six and so on," he continues. "This silly story illuminates the way that a wormhole would naturally destroy itself."

Owen is talking about feedback, just like the feedback you might get on a microphone, because it's not just people that could take a trip though these time-tunnelling wormholes. Radiation, be it light or heat, can also enter the wormhole and do exactly the same thing as the multiple Robert Owens. So much energy would end up in the loop that it would cause the wormhole to collapse.

Another problem is that a wormhole would be too small for a single person – let alone a spaceship capable of interstellar travel – to be able to comfortably fit through. To successfully pass through a hole, we would need to find some way of enlarging one, something that seems unfeasible given that we don't even yet have proof of its existence.

However, not everyone thinks that the journey would be impossible. One of the world's leading theoretical physicists, Kip Thorne, is professor emeritus at the California Institute of Technology (Caltech) and a long-time friend of both the late Stephen Hawking and Carl Sagan. Thorne not only thinks that these portals might exist, but that they could also be used as some kind of time machine, capable of getting us from one place in the universe to another.

Another scientist who has confidence in the possibility of using wormholes for travel is Eric Davis, a senior research physicist at the Institute for Advanced Studies at Austin, Texas. "All you need to enter a wormhole is a spacecraft. Just dive in and go," he says. "If the wormhole is too small for a spacecraft, then it has been posited by Kip Thorne, the man who discovered suggestions of traversable wormholes in Einstein's theory of general relativity, that all one may need to do is feed the wormhole more negative energy density and/or more-negative pressure to inflate it up to a larger size."

So, what is negative energy? Dark energy, which is causing the universe to expand, is an example of a negative energy pressure

WHY ARE WE LOOKING FOR WORMHOLES?

Professor Robert Owen, of Oberlin College, USA, tells us why hunting for wormholes is so necessary

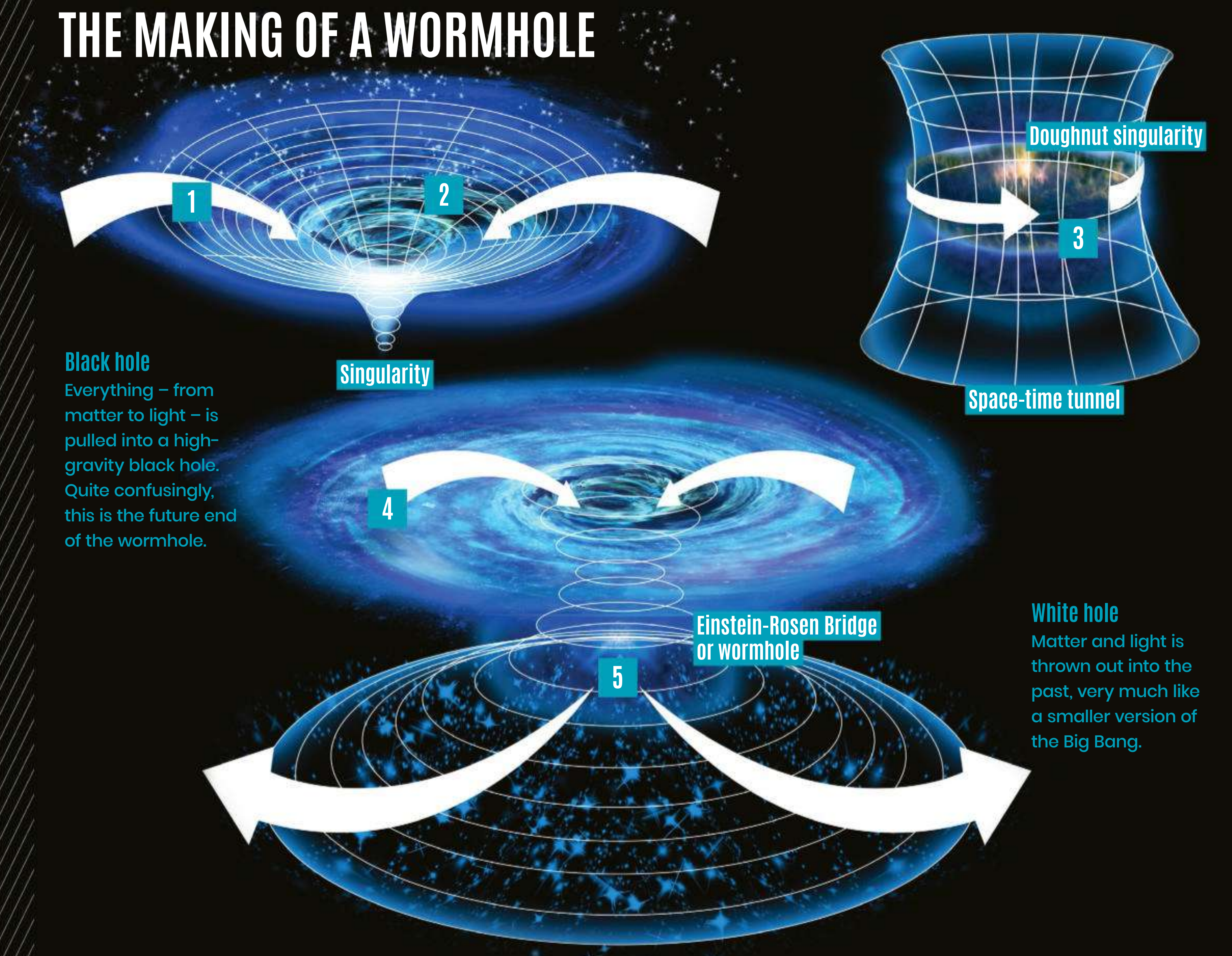
"I think it's extremely important that we continue to search for and research the ideas behind wormholes. There are all sorts of [avenues for] research and we often find that some subjects are more practical than others. Obviously wormhole physics is not a very practical subject, but wormholes and other exotic phenomena provide a route to understanding some of the deepest questions about the nature of our universe. For that reason alone, this is an exciting endeavour and deserving of support.

"It's also important to note subjects that might seem highly impractical could eventually be central to our daily lives. Electromagnetic theory was at one time considered an impractical subject and now it's fundamental to everyday life. Quantum theory has long been viewed as an arcane body of research, but now it's essential for the inner workings of much modern technology.

"All research is fundamentally interconnected, with insights made in one field of study often transferred. For example, there is a long-standing symbiosis between research in particle physics and solid-state physics – the field that provides much of our understanding of the properties of materials. There is a constant conversation between these two fields of study and ideas are regularly shared between them.

"Einstein's general theory of relativity predicts quite clearly that if a wormhole existed, it would be unstable and we wouldn't be able to use it for travelling through time. However, with all scientific questions, we can't be completely certain that general relativity is the most accurate possible description of space-time in all situations. It could be that in certain situations general relativity becomes inaccurate, just as Newtonian physics becomes inaccurate near a black hole, for example. This means I certainly wouldn't rule out the idea absolutely, until we have some good astronomical evidence."

THE MAKING OF A WORMHOLE



1 Collapse of the core

When a gigantic star dies, when it no longer has any nuclear fuel to burn, sometimes a black hole is formed. The core has no choice but to collapse in on itself in the catastrophic explosion of a supernova. The devastated star's outer layers are expelled into space, while the core continues to shrink in size.

2 A cosmic plug hole

Shrinking smaller and smaller, the core continues to pale in significance. While it has shrunk to a speck, all of its mass is concentrated in a very small area. This forms a singularity. If you place anobject onto a bed sheet, it makes a dent. Anything moving towards the dent will fall towards it, which is how gravity affects the universe.

3 The makings of a doughnut

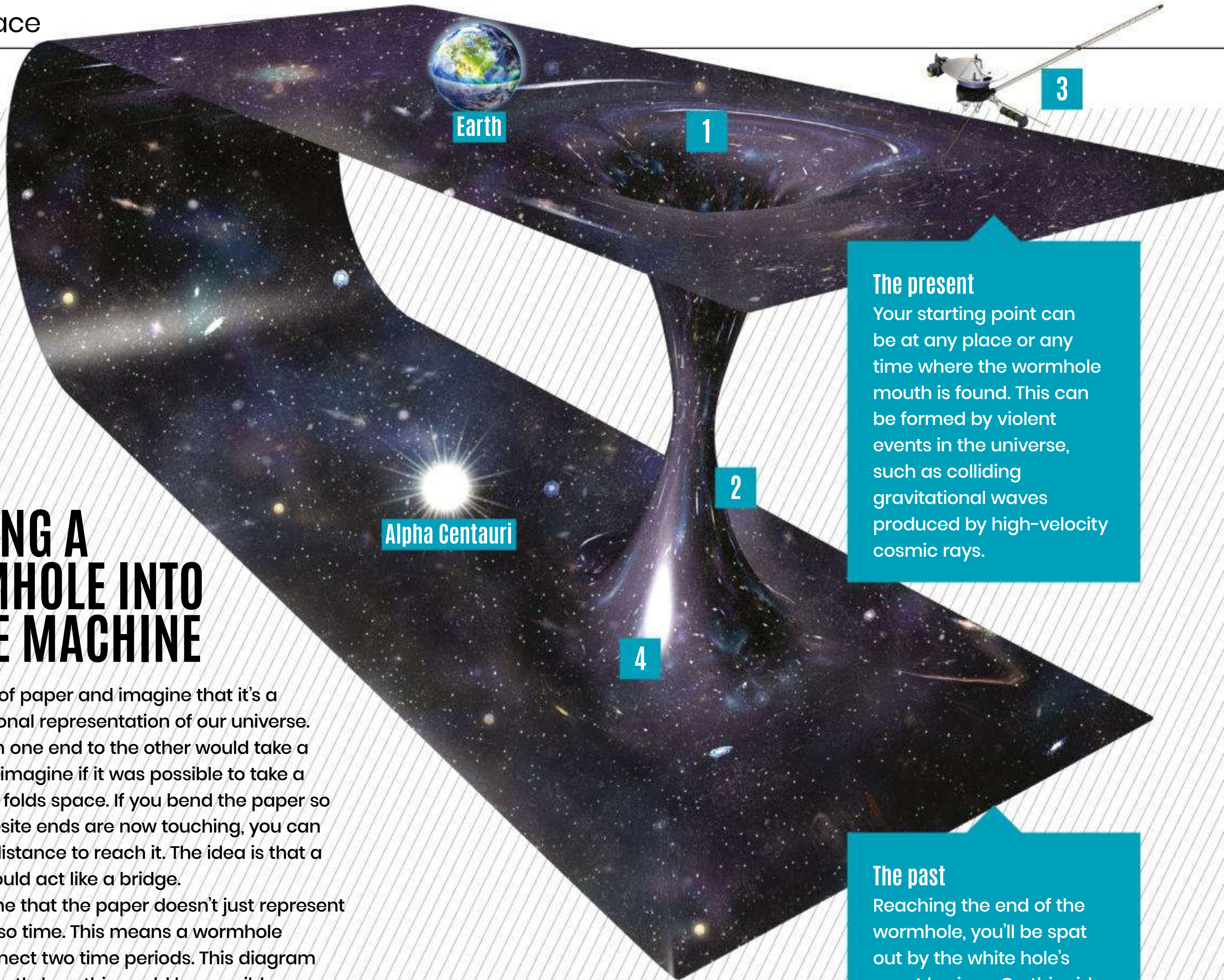
A star's core can still be found to be spinning when it decides to collapse. Crumbling to a singularity, it rotates faster and faster, spinning so fast that what's left of the star's material spreads out. Space-time is no longer focused on a single point, but is being wrapped around space ring.

4 Punching through space

The tunnel punches its way through the fabric of space-time and, almost in an unusual state of reversal, emerges backwards in time and into the past. This tunnel, which can work its way into another parallel universe, is called an Einstein-Rosen bridge, or wormhole. Any matter grabbed by the black hole is passed through t his tunnel.

5 Exit

If you were to travel through a wormhole, you would reach its far side, which can be likened to a black hole in reverse: the white hole. Matter pulled in by the black hole will emerge from the singularity found at the white hole's centre and released.



The present

Your starting point can be at any place or any time where the wormhole mouth is found. This can be formed by violent events in the universe, such as colliding gravitational waves produced by high-velocity cosmic rays.

TURNING A WORMHOLE INTO A TIME MACHINE

Take a piece of paper and imagine that it's a two-dimensional representation of our universe. To travel from one end to the other would take a long time, so imagine if it was possible to take a shortcut that folds space. If you bend the paper so the two opposite ends are now touching, you can hop a short distance to reach it. The idea is that a wormhole would act like a bridge.

Now imagine that the paper doesn't just represent space, but also time. This means a wormhole can also connect two time periods. This diagram illustrates exactly how this could be possible.

The past

Reaching the end of the wormhole, you'll be spat out by the white hole's event horizon. On this side you would have travelled both backwards in time and onto the other side of the universe – if you're even in the same one you started in, that is. Estimations of where a wormhole could take you are beyond even our best theories at present.

1 Enlarging the mouth

To enlarge the mouth, you would need exotic matter – in other words something with negative energy to act as an anti-gravity to hold the wormhole open.

2 The throat

Between the two mouths of the wormhole is a throat that acts as the bridge across space and time.

3 The traveller

Stable and traversable wormholes would need to be big enough for a person or a spaceship to travel through them.

4 Mouth of the wormhole

Scientists call this a closed time-like curve – a loop that connects the two different periods of time found at each mouth of the wormhole.

– something that is opposing forces such as gravity. However, we don't even know what dark energy is, let alone how to create true negative energy, so we won't be venturing down a wormhole any time soon.

Still, this isn't to say that nature hasn't found a way to enlarge wormholes, which is exactly what Russian scientists working on Project RadioAstron are banking on. They are using the largest space telescope ever launched – not Hubble or the Herschel Space Observatory, but Spektr-R, a radio telescope that launched into space in 2011 and has a detector diameter of ten metres (33 feet). The hope is Spektr-R will discover evidence for wormholes and white holes.

The project's initial steps into probing the universe were originally quite bleak, because the Soviet Union collapsed just as it was within reach of being completed, but now it has been restarted. Until quite recently an old radio telescope built in 1959, dubbed RT-22, was the main receiver of signals from the Spektr-R. For many months the receiver has been studying supermassive black holes found at the centres of galaxies and even probing the Milky Way's own black hole, Sagittarius A*. Observations of the black hole's event horizon – the point of no return from this exotic high-gravity beast – is where RadioAstron's aims get interesting.

Getting close to black holes could lead us to the elusive wormholes and white holes, according to RadioAstron scientists. The trick is to keep our eyes peeled for a certain signature. "We must look for the structure of magnetic fields near the centres of galaxies," says Novikov, who back in 1964 also pointed out that general relativity allows for the

existence of white holes. "If the structures of the magnetic fields appear to be magnetic monopoles, that are macroscopic in size, then this is a wormhole. [These magnetic phenomena have only one pole and are predicted to exist but so far, like wormholes, have proven elusive]." It turns out that wormholes – specifically their white holes – will emit their own radiation, in contrast with black holes that don't emit radiation, but rather intensive radiation from the surrounding gas that spews out in swirls.

We might not have detected a wormhole for sure, but RadioAstron might be on to something. Turning its attention to the core of quasar 3C273, in the constellation Virgo around 2.5 billion light years away, it has found something unexpected. Quasars are active galactic nuclei producing enormous amounts of radiation from around their black holes. We know there's a black hole in the heart of 3C273, but RadioAstron's observations show that it has increased in temperature. There's also the magnetic field that Novikov mentioned earlier, so RadioAstron must verify the suspicions of theoretical physicists.

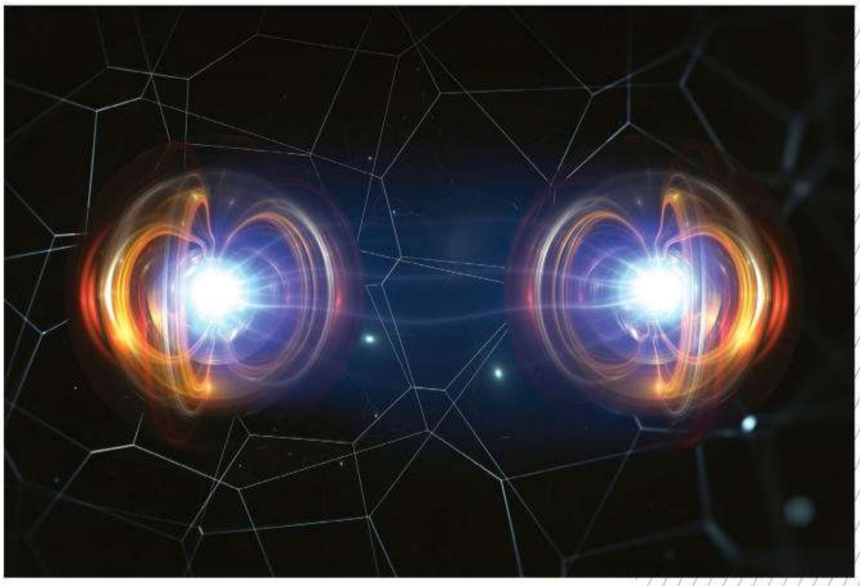
Meanwhile, instead of using telescopes to scan the skies for these tunnels, other astrophysicists have taken to imagining wormholes. For example, physicists Jensen and Karch have suggested that the particles of a quantum phenomena called entanglement are connected by miniature wormholes. When two particles interact they can become entangled so their characteristics correlate. The Heisenberg Uncertainty Principle means that the quantum states, or properties of the particles such as their spin, remain undefined until they're measured properly. However, when the spin of one of the entangled particles is measured, the other particle instantly follows suit, even if each of them are on opposite sides of the universe at the time.

How they communicate across huge distances so quickly is not truly understood, but Karch and Jenson have proposed that tiny black holes that have become entangled may have wormholes connecting them. Julian Sonner of the Massachusetts Institute of Technology has taken this idea a step further, showing that wormholes could connect entangled quarks, which are the fundamental particles that make up protons and neutrons inside of atoms.

Another place where theorists are looking for wormholes is inside stars, although their location might make it difficult for us to reach them. Vladimir Folomeev of the Institute of Physicotechnical Problems and Material Science in the Kyrgyz Republic (Kyrgyzstan) has suggested that if exotic phantom matter exists then it's possible it could exist within stars.

"The idea is very simple," explains Folomeev. "If dark energy amounts to about 70 per cent of the total energy density of the universe, then it is natural to assume that in some cases mixed objects consisting of both ordinary matter and dark energy can exist." A mixed star would act oddly, affecting the star's mass and causing oscillations.

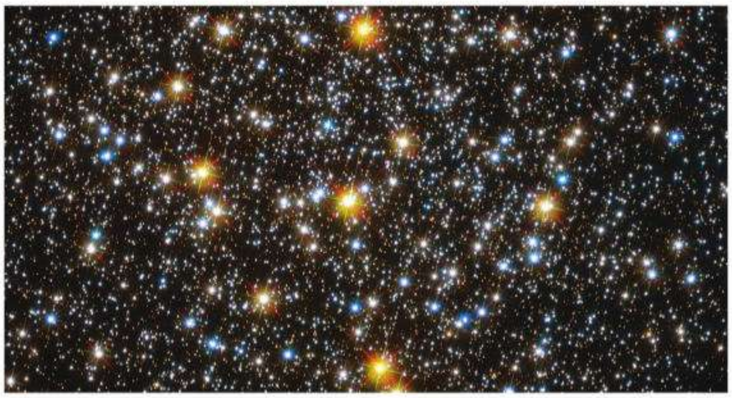
There are many places that wormholes could be hiding, from inside black holes and stars to the subatomic world, but what would it be like to travel down one? According to Davis, the mouth would look like a sphere with a distorted mirror image of the region of space on the other side of the wormhole, as the negative energy density deflects light passing through. When you pass through, the journey would likely be instantaneous and looking back you'd see another sphere reflecting where you came from. Across the universe in a single step – wormholes would be a truly giant leap.



"It is natural to assume that in some cases mixed objects consisting of both ordinary matter and dark energy can exist"

Vladimir Folomeev

An artist's impression of quantum entanglement. If two photons of light are allowed to properly interact with each another, they can become entangled



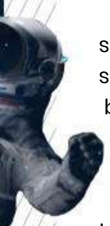
How many of the stars out there in the universe could harbour wormholes at their centres?

20 UNIVERSE MYTHS BUSTED

Think you know all about space? Here are 20 myths about the universe that need debunking

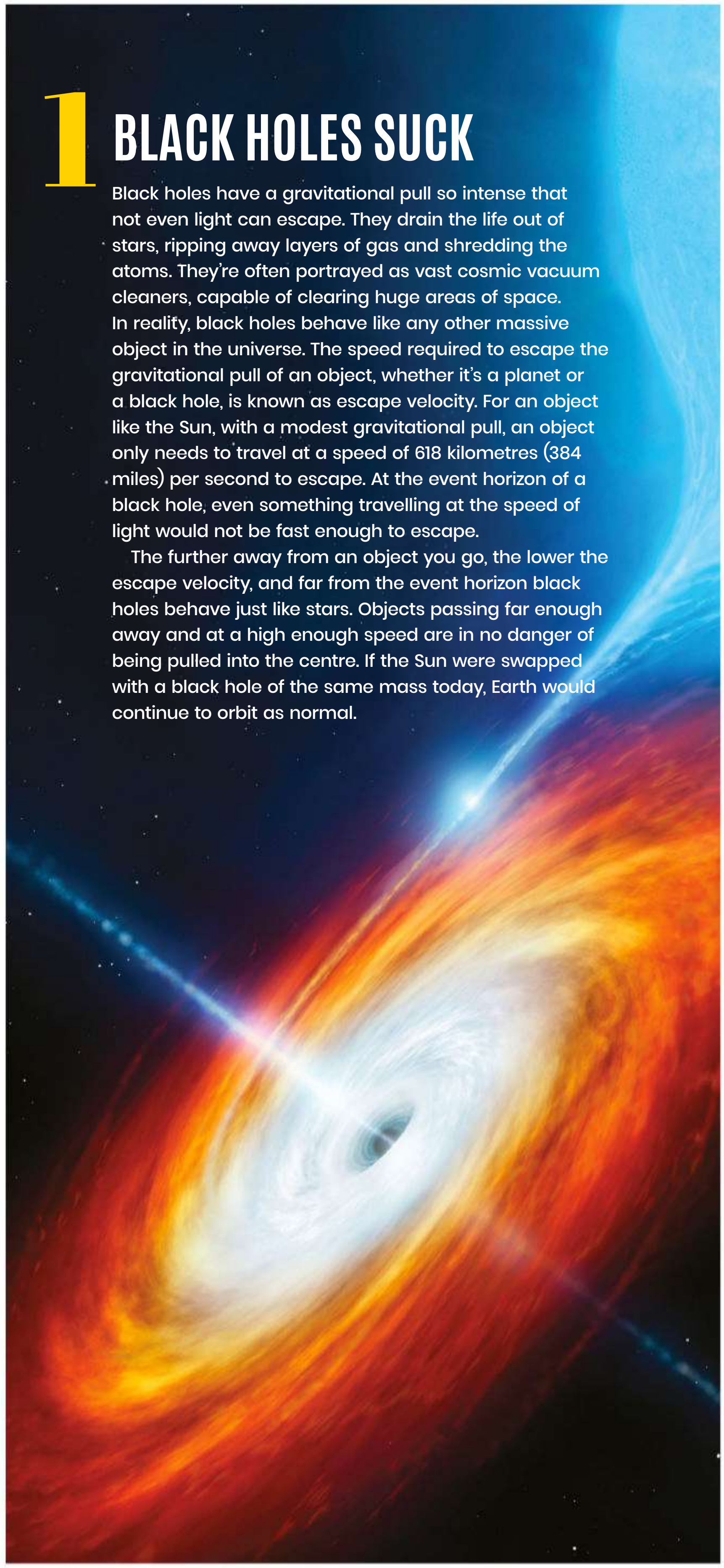
Written by Laura Mears

Our understanding of the workings of the universe is better than it has ever been, but there are still a number of misconceptions that manage to fool many of us. Some of the following might sound plausible, but barely any of it is true: the Sun is a burning orb of yellow fire and the temperature is higher during the summer months because we orbit closer than we do in winter. Mercury is the closest planet to our star and must therefore be the hottest.



The lunar phases are caused by the shadow of Earth and at night we can only see one side of the Moon, so the other must be in perpetual darkness. The stars form patterns with their close neighbours and are grouped into local constellations. The twinkling light that they produce travels to Earth in a straight line, unaffected by the pull of gravity. Comets race past with their tails pointing back towards the direction that they came from, and as meteorites tumble through the atmosphere, they heat up so much that it's not safe to pick them up from the ground.

In space, astronauts experience zero gravity and the only human-made object they can see is the Great Wall of China. Friction on re-entry heats their spacecraft to thousands of degrees, and if the astronauts were unfortunate enough to have a collision in space, it would make an audible bang. Any astronaut exposed to the vacuum of space without a spacesuit would explode due to a pressure imbalance. Saturn is the only planet with rings, but in order to reach it you have to travel through the asteroid belt, which is so packed with rocks that it is like a minefield. And watch out for black holes, because they'll suck you straight in.



1 BLACK HOLES SUCK

Black holes have a gravitational pull so intense that not even light can escape. They drain the life out of stars, ripping away layers of gas and shredding the atoms. They're often portrayed as vast cosmic vacuum cleaners, capable of clearing huge areas of space. In reality, black holes behave like any other massive object in the universe. The speed required to escape the gravitational pull of an object, whether it's a planet or a black hole, is known as escape velocity. For an object like the Sun, with a modest gravitational pull, an object only needs to travel at a speed of 618 kilometres (384 miles) per second to escape. At the event horizon of a black hole, even something travelling at the speed of light would not be fast enough to escape.

The further away from an object you go, the lower the escape velocity, and far from the event horizon black holes behave just like stars. Objects passing far enough away and at a high enough speed are in no danger of being pulled into the centre. If the Sun were swapped with a black hole of the same mass today, Earth would continue to orbit as normal.

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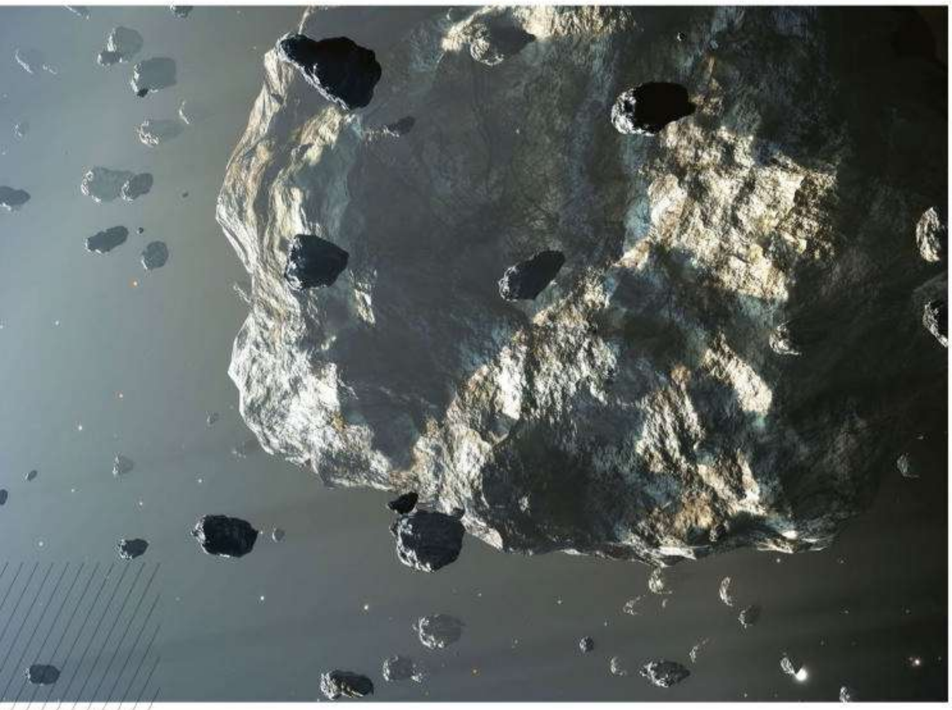


2 THE ASTEROID BELT IS VERY HAZARDOUS

There's no doubt that there is a lot of rock in the area of our Solar System that's known as the asteroid belt. Sitting between Mars and Jupiter, this band of fragments contains over 3,000 minor planets and more than 750,000 separate asteroids measuring more than 1,000 metres (3,280 feet) across. The larger asteroids sometimes collide, spraying smaller fragments into the belt – according to myth, endangering any spacecraft that dares to weave its way through. This myth has been fuelled by science fiction. When Han Solo takes the Millennium Falcon into an asteroid field in *Star Wars: The Empire Strikes Back*, C-3PO warns: "Sir, the possibility of successfully navigating an asteroid field is approximately 3,720 to one". If the Hoth asteroid field is anything like our own, he couldn't have been more wrong.

In the 1970s, NASA's Pioneer 10 became the first spacecraft to navigate its way through the asteroid belt. Only a layer of aluminium honeycomb protected the spacecraft, but despite the apparent danger, it made it's way through with no trouble. Not because of careful evasion, but because the distance between asteroids is huge. On average, there's a distance of around 970,000 kilometres (600,000 miles) between the asteroids, which is more than twice the distance from Earth to the Moon. When compared to the crowded space imagined in the movies, the asteroid belt is actually relatively empty. A much bigger danger in the asteroid belt is the dust-sized particles that form when asteroids collide. These tiny grains could definitely cause damage to spacecraft, but evading rocks the size of a grain of sand doesn't make for very good television.

"This band of fragments contains over 3,000 minor planets"

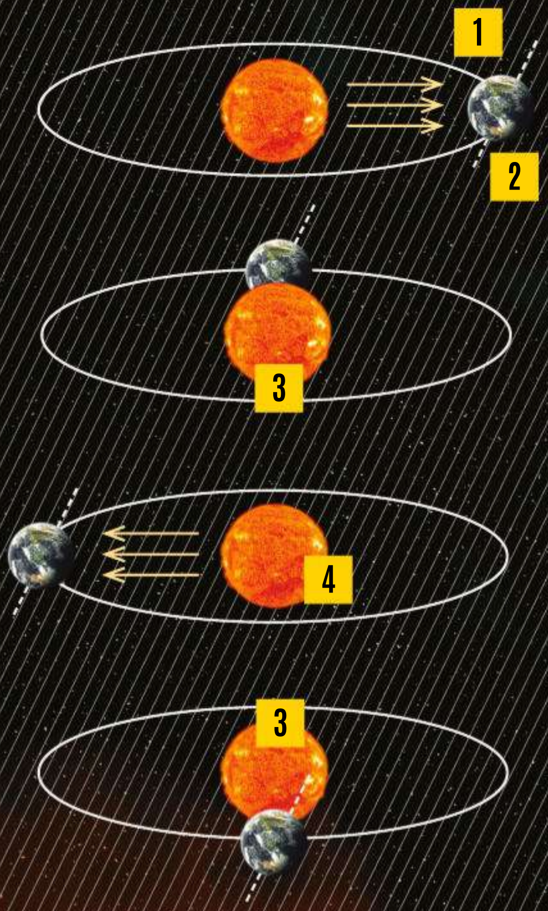
3 THE SUN IS YELLOW

Though you should never look directly at the Sun, photographs reveal a yellowish hue. The Sun produces all wavelengths of visible light, and therefore its true colour is white, but as sunlight travels through the atmosphere it changes. The wavelengths of light at the blue end of the spectrum are much shorter than those at the red, so collisions with particles in the air are more likely. During the day, blue light scatters high in the atmosphere, giving the sky its blue colour and making the Sun appear yellow. In the morning and evening, the light that hits the ground has farther to travel, so this effect becomes more extreme. Most of the shorter blue wavelengths scatter before they hit the ground, giving sunrise and sunset their characteristic red-orange hue.

4 EARTH IS CLOSER TO THE SUN IN SUMMER

Most people know Earth doesn't travel around the Sun in a perfect circle, so it's easy to see why some make the leap and assume that the seasons are caused by the distance to the Sun, but the idea doesn't hold up when you think that the Northern and Southern Hemispheres experience summer at different times of the year. Earth's orbit isn't as elliptical as people imagine. Over the course of a year, the distance between Earth and the Sun varies by just 5 million kilometres (3.1 million miles) – that's only about three per cent. What's more, during winter in the Northern Hemisphere, we're actually closer to the Sun than we are in summer.

The real reason for the seasons is the axial tilt of Earth. As the year progresses, light hits the Northern and Southern Hemispheres at proportionally different angles and for different amounts of time every day. During winter, the days are short and the light strikes the atmosphere at a low angle, glancing through the gases as it travels towards the surface and spreading out as it reaches the ground, distributing the energy. During summer the days are much longer and the sunlight hits Earth at a steep angle, taking a more direct path towards the floor and concentrating the energy into a smaller area.



1 December
In December the Northern Hemisphere tilts away from the Sun. Day lengths are shorter as a result.

2 Axial tilt
Earth's axis points in the same direction. As the year goes by, different parts of Earth end up facing the Sun.

3 March and September
In spring and autumn, the axis is lined up parallel to the Sun. The length of a day evens out.

4 June
The Northern Hemisphere receives direct sunlight and the days are longer, raising the temperature.

5 THE SUN IS BURNING

Fire needs three things to survive: fuel, heat and oxygen. The Sun has fuel, as it's composed mainly of hydrogen and helium gas. Helium is an inert element and doesn't burn like some of its volatile neighbours on the periodic table, but hydrogen is highly flammable. The Sun also has an enormous amount of heat energy – its surface is an Earth-melting 5,500 degrees Celsius (9,932 degrees Fahrenheit). However, there's no oxygen in space, so the fire triangle is incomplete for the Sun.

In reality, the Sun isn't actually a ball of fire. Instead, the heat and light that it produces are the result of thermonuclear fusion. Inside the high-pressure, high-heat environment of our star, high-speed hydrogen atoms come within one femtometre of each other – that's 0.000000000000001 metres. A collision at this distance allows the two nuclei to fuse together, forming helium and releasing huge quantities of energy as gamma-ray radiation.

6 THE MOON HAS A DARK SIDE

The dark side of the Moon has inspired studio albums, novels, television series, films and video games, but the Moon itself is not quite what it seems. We only see one side of the Moon from Earth, but just because we can't observe the other side, it doesn't mean that it's dark.

Looking at the phases of the Moon easily disproves this myth. During a full Moon, the side that we can see is fully illuminated and the other side really is in complete darkness, but at any other time of the month we can only see part of the Moon. The rest of the light is falling on the far side, or the so-called dark side.

For photographic evidence, you only have to look at the first-ever images of the far side of the Moon, captured in 1959 by the Soviet Union's Luna 3, showing how it was perfectly lit up by the Sun. Not only do these images dispel the myth that the dark side of the Moon receives no light, they also show that the rock is actually lighter in colour than the side that we can see, making our side the true dark side.

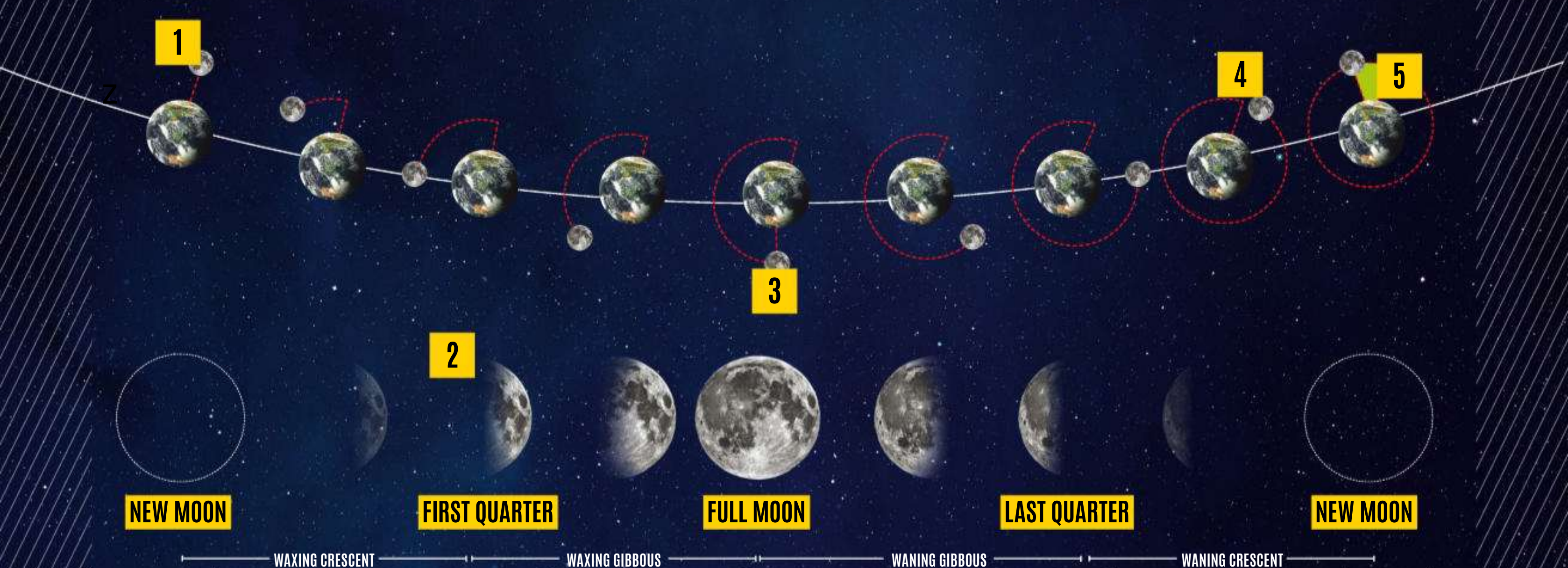
1 New Moon
At the start of each lunar cycle, the Moon comes between Earth and the Sun, so the Sun's light is actually illuminating the dark side.

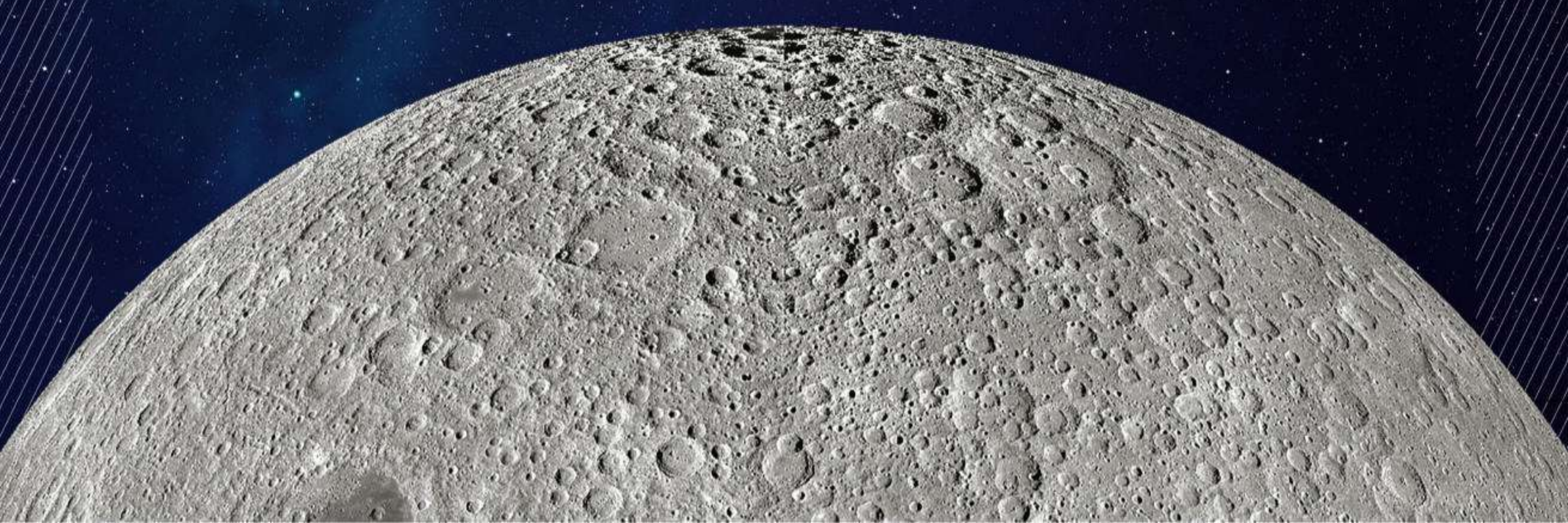
2 Half lit
As the Moon waxes and wanes, light falls on both the near side and the far side of the Moon at the same time, so we only see part of it.

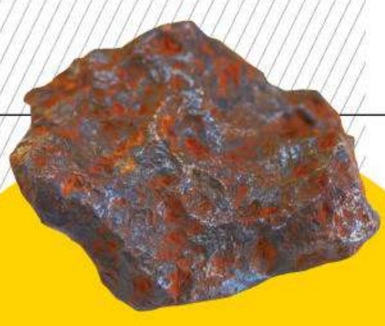
3 Full Moon
By the time the Moon has completed half of its orbit, it's fully visible in the sky. The side that we see is directly facing the Sun and the dark side really is dark.

4 Full circle
By the time the Moon has completed an orbit around Earth, its entire surface has been exposed to the Sun, meaning that there's no literal dark side.

5 View from Earth
The Moon is tidally locked to Earth, meaning that as it orbits it spins to face us so we only ever see the same side. The other side is commonly known as the dark side.







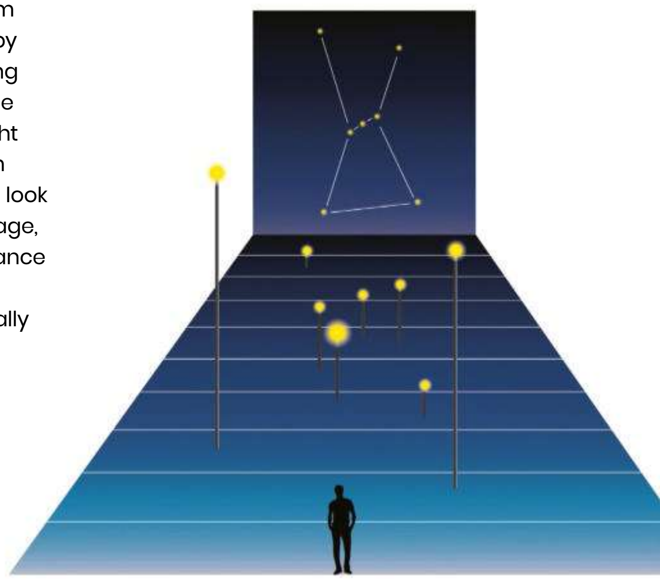
7 METEORITES ARE HOT

As meteorites pass through the atmosphere, they heat up so rapidly that the surface rock begins to melt. However, it's a bit like searing a steak: although the outside becomes intensely hot, the inside remains cool. The melted rock forms a crust just a millimetre (0.04 inches) thick. By the time a meteorite hits Earth, it is likely to be only slightly warm to human touch.

8 STARS IN CONSTELLATIONS ARE CLOSE TOGETHER

The stars in the night sky are arranged into 88 constellations that represent, among other things, 29 inanimate objects, 19 land animals, nine birds and a dragon. These recognisable groupings have guided farmers and travellers for thousands of years, but in terms of proximity they're not really groups of stars at all. Despite appearing to be close together, the stars that form the constellations are often separated by tens or hundreds of light years, extending backwards into space. From our vantage point on the surface of Earth, Orion might look like a warrior with a shield, but from elsewhere in the galaxy the stars would look distant and unconnected. They vary in age, size, type and brightness, and it's by chance that we see them in groups.

Constellations might not be scientifically meaningful groups of stars, but they do help break up the sky into recognisable and manageable chunks. By making associations between patterns in the stars and familiar animals or objects, the names and positions of individual stars suddenly become much easier for astronomers to remember. This is one of the few occasions when myths can be a good thing, because the mythology and stories surrounding each of the constellations helps fix them in people's minds.



9 EARTH'S SHADOW CAUSES THE LUNAR PHASES

It seems plausible that the lunar phases are the result of Earth's shadow, but the Moon is often visible alongside the Sun during the day, so what's really causing the lunar phases? They're actually the result of the Sun rising and setting over the visible side of the Moon as it orbits Earth. During a full Moon, our satellite is on the opposite side of Earth to the Sun, so we see the sunlight illuminating its entire visible surface. However, during a new Moon the Moon comes between Earth and the Sun, so the light falls on the side that we cannot see. In the intervening days, the amount of light that we can see on the lunar surface gradually increases and decreases with the orbit of the Moon.

A lunar eclipse is the only time that Earth casts a shadow on the Moon, and these rare events only occur if Earth comes exactly between the Sun and the Moon, temporarily blocking out the light.

10 YOU CAN SEE THE GREAT WALL OF CHINA FROM SPACE

The Great Wall of China is the longest human-made structure in the world and spans an incredible 21,196 kilometres (13,171 miles). The idea that it might be visible from outer space is a popular one and has been around since the 1930s, but unfortunately it is only partly true.

The Great Wall might be very long, but it's not remotely as wide – just over six metres (20 feet) at its base. Not only that, it's constructed from materials that blend well with the surrounding terrain. In low-Earth orbit, which starts at 160 kilometres (99 miles) altitude, the wall is easy to pick out on radar images but is invisible to the naked eye. During his time on the International Space Station (ISS) in March 2013, Chris Hadfield tweeted: "I did not see the Great Wall of China from space and neither did the Chinese astronauts. With a big enough camera lens and clear air, maybe."

11 RE-ENTRY SPACECRAFT HEAT UP BECAUSE OF AIR FRICTION

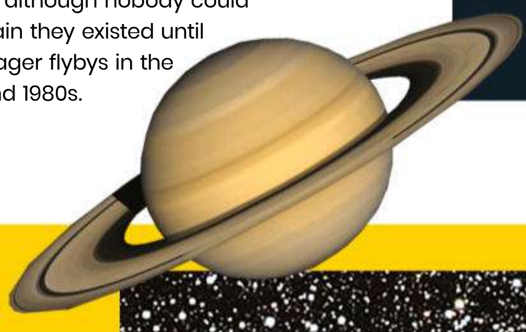
As a wide, blunt spacecraft plummets through the atmosphere, molecules of gas cannot move out of the way fast enough and they start to stack up, forming a cushion beneath the craft. This keeps most of the gas away from the surface, preventing heat from transferring to the vehicle. Frictional heating contributes to the temperature rise, but the pressure achieves the real heating. The closer the compressed molecules come to one another, the higher the temperature climbs. Eventually, the pressure becomes so intense that the molecules start to tear apart, creating a layer of charged plasma and producing a searing plasma corona.

12 MERCURY IS THE HOTTEST PLANET IN THE SOLAR SYSTEM

Venus, which orbits nearly twice as far from the Sun as Mercury, has an average temperature of 462 degrees Celsius (864 degrees Fahrenheit). The difference is down to the atmosphere. On Venus, the atmosphere is thick and composed mainly of carbon dioxide, trapping the heat in an insulating bubble, while Mercury has a very thin atmosphere.

13 SATURN IS THE ONLY RINGED PLANET IN THE SOLAR SYSTEM

When people think of planets with rings, there's only one that springs to mind. Saturn is well known for its seven main rings. There's no denying that they are incredibly photogenic, but they aren't the only ones in the Solar System. Jupiter, Uranus and Neptune all boast their own set of rings, although nobody could be certain they existed until the Voyager flybys in the 1970s and 1980s.



14 STARS TWINKLE

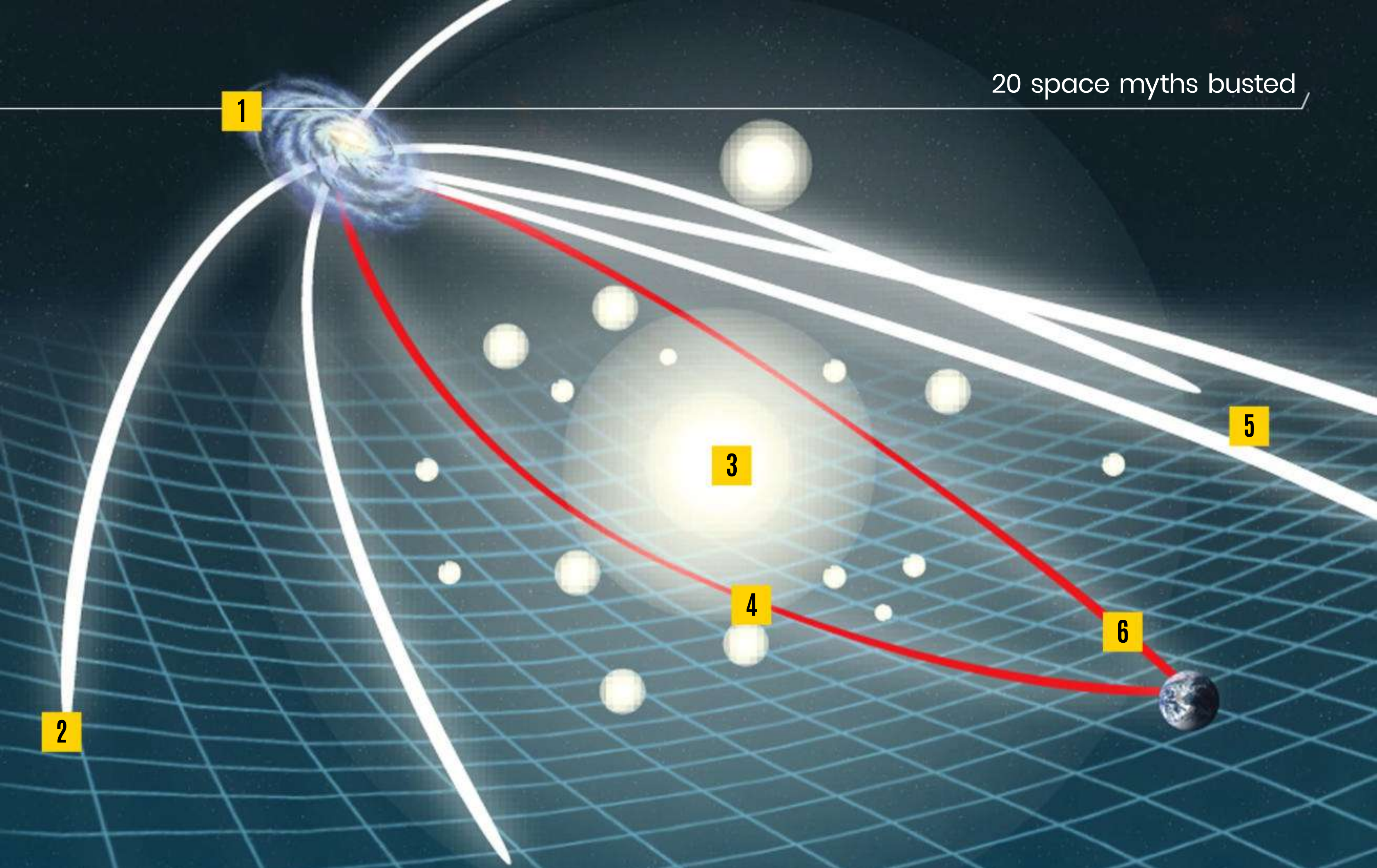
A famous nursery rhyme is responsible for this myth, but although stars appear to twinkle in the sky, the flickering is just an illusion. It might seem plausible that a star would twinkle as it shines, but at this distance the light that we see from them is actually very steady.

As light travels towards Earth, it passes through the gas molecules that make up our atmosphere. These are not static and they swirl as turbulence stirs the atmosphere. This deflects some of the light, making it look like the light is shifting and twinkling. The more atmosphere the light has to pass through, the more likely these shifts are to occur, making stars near the horizon appear to twinkle more.

15 LIGHT ISN'T AFFECTED BY GRAVITY

Gravity is an attractive force between two objects with mass, and light is transmitted by photons, which have no mass, so light can't possibly be affected by gravity. But if this is true, how is it that black holes can prevent light from escaping? The laws of gravity were the work of Isaac Newton, who said that gravity is a pulling force that works when both objects involved have mass. However, Albert Einstein overhauled this theory by suggesting it was the result of the shape of the fabric of the universe.

Imagine placing a heavy ball on a sheet of rubber. The rubber stretches, creating a dent. If you try to roll a smaller ball from one side of the sheet to the other, instead of travelling straight, it will have to curve. This is what the stars and planets do to the dimensions of space-time. These curves don't just affect objects with mass, but light travels so fast that the dips in space-time have little effect on it. But black holes create space-time curves that bend towards infinity, so not even light can climb out the other side.



1 Galaxy The light from distant galaxies can be seen from Earth, but the pictures that we capture don't always match what is really there due to gravitational lensing.

2 Cosmic magnification This phenomenon is known as gravitational lensing because the curve in space-time bends light like a lens.

3 Galaxy cluster This massive cluster of galaxies between Earth and the distant galaxy has created an enormous curve in space-time.

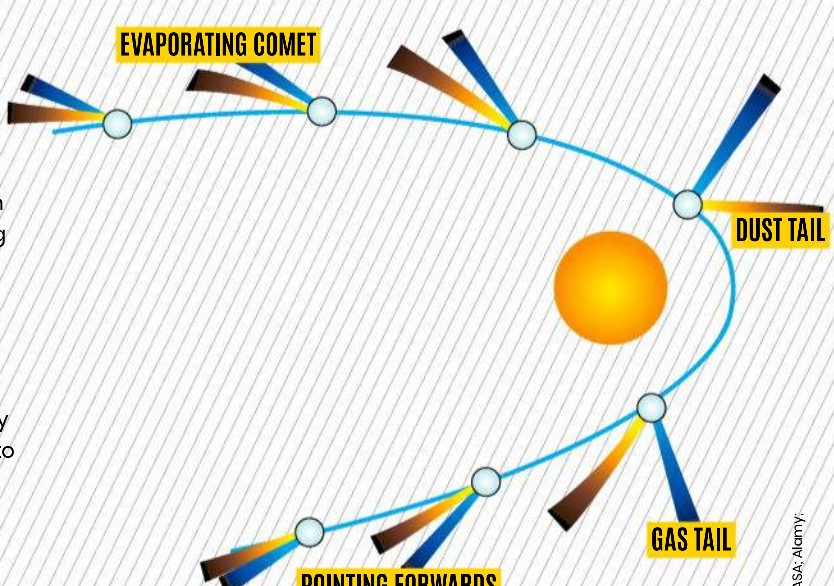
4 Lensed image The path of the light is bent so much that the image appears more than once in the sky – as a duplicate or as streaks or rings.

5 Space-time This two-dimensional representation of space-time gives an idea of what is really happening in the four dimensions of space and time.

6 Bent path The photons of light released by the distant galaxy curve their paths as they travel past the massive cluster of galaxies.

16 COMET TAILS INDICATE WHICH WAY THEY'RE HEADING

Comets are essentially lumps of dirty ice. As they approach the Sun they heat up, releasing gas and dust. We would expect the resulting tail to point backwards, like the streak of a falling meteor, but in space there's no air. Comets are shaped and blown by radiation pressure and the solar wind, so they always point away from the Sun. High-energy ultraviolet light crashes into the evaporating gas of the comet, stripping away electrons and forming charged ions. These get caught up in magnetic field lines and shoot directly away from the Sun in a blue ion tail. At the same time, dust is released into space, forming a tail of particles as fine as smoke. Photons of light from the Sun create an intense bubble of pressure which pushes against the dust, guiding it into a wide streak that curves around the path of the comet's speedy orbit.



17 YOU CAN HEAR SOUNDS IN SPACE

The sound of an exploding vehicle on Earth is transmitted by a pressure wave, which travels through fluids like air or water when vibrating particles bump into one another and pass some of their energy on. In space the particles are so far apart that sound waves cannot propagate, so although the source of an explosion would vibrate, the movements have nowhere to go. Outside of Earth, only on planets with atmospheres would we hear sound.

18 SPACE IS AN EMPTY VACUUM

Space is closest to a true vacuum in the universe and is far emptier of any particles than anything we can produce on Earth. However, there's so much hydrogen in the universe that a few atoms can still be found in every cubic metre of space. It's a vacuum compared to the atom-rich atmosphere of Earth, but it's not perfect. Nowhere in space can be guaranteed to be a true vacuum in the strictest sense.

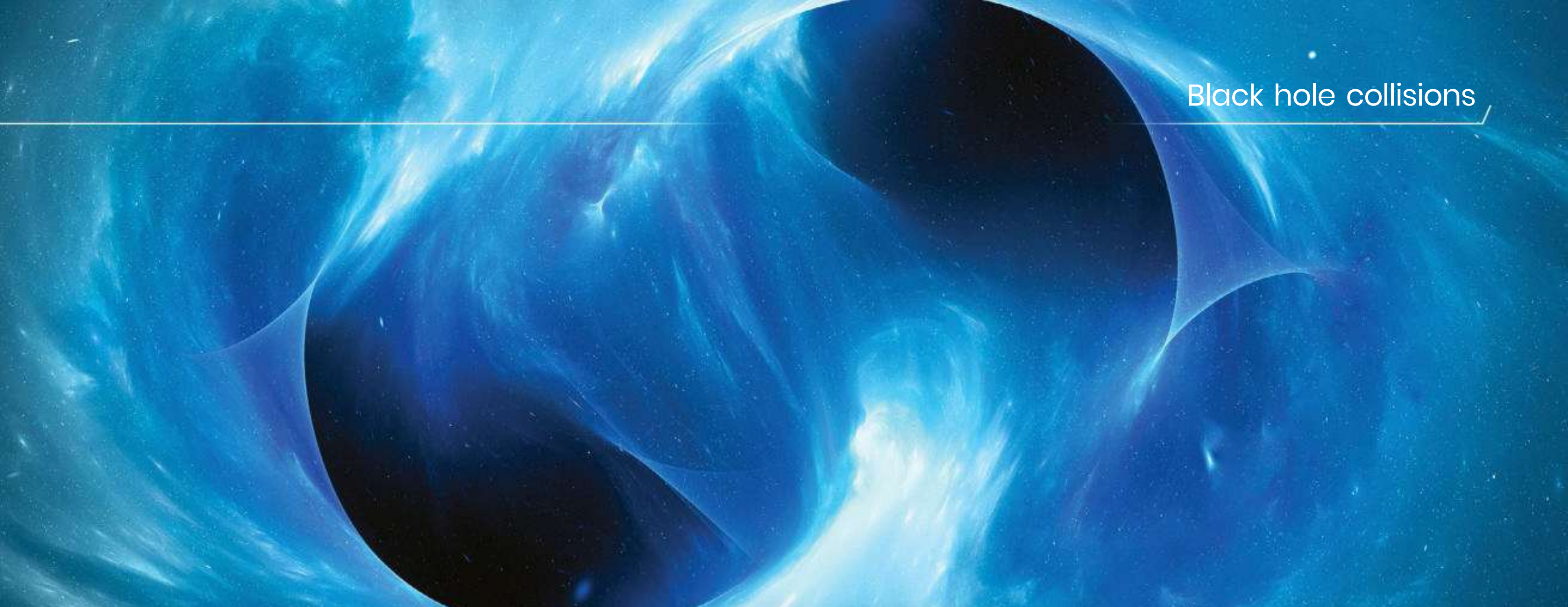
19 THERE'S NO GRAVITY IN SPACE

Craft like the ISS are constantly under the influence of Earth's gravity – that's what keeps them in orbit. The weightlessness that the astronauts experience is because they are falling gradually towards Earth. Gravity compels the ISS towards the ground, but the space station is moving so quickly that it shoots over the horizon, falling around the curvature of the planet instead of coming back down to Earth – essentially, the astronauts inside are in a constant free fall.

© NASA

20 WE EXPLODE IN SPACE WITHOUT A SPACESUIT

Our bodies are adapted to exist under the pressure of Earth's atmosphere. When this is removed, water in our tissues starts to evaporate and the body starts to swell. Human skin is stretchy enough that this does not lead to an explosion, but after around ten seconds of exposure, people become unconscious. This happened to an unfortunate spacesuit technician during a NASA test in 1966 after some equipment failed, but thankfully the pressure was restored after just 30 seconds and the technician recovered.



FOCUS ON

BLACK HOLES SPOTTED ON A COLLISION COURSE

NASA's Chandra X-ray Observatory has seen the first evidence of black holes in dwarf galaxies about to impact

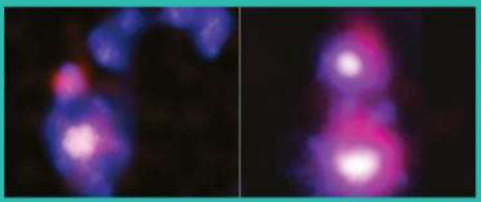
Reported by Robert Lea

Astronomers have spotted not one but two dwarf galaxy black hole duos on separate collision courses, the first observational evidence of such a cosmic clash. Just as the black holes are heading for a collision and merger that will leave a more massive black hole behind, the dwarf galaxies they sit in will also merge and form a larger galaxy. The findings could have important implications for our understanding of how these cosmic titans and the galaxies they inhabit grew in the early universe. Scientists examined the colliding black hole pairings using NASA's Chandra X-ray Observatory and found that as the dwarf galaxies are racing towards each other, they are pulling in gas that is 'feeding' their inhabitant black holes, causing them to grow even before the merger.

Dwarf galaxies are small galaxies that contain stellar mass equivalent to no more than around 3 billion times that of the Sun. By comparison, the entire Milky Way is believed to contain a stellar mass around 60 billion times that of our star. Scientists think that in the first hundreds of millions of years after the Big Bang, the early universe was replete with these dwarf galaxies, most of which merged to form larger galaxies like ours.

These early galaxies have thus far been impossible to observe due to the fact they are extremely faint and are located at great distances away. Astronomers have, however, seen closer dwarf galaxies in the process of merging, but there has been no sign of black holes in those galaxies until now. "Astronomers have found many examples of black holes on collision courses in large galaxies that are relatively close by," Marko Micic, a researcher at the University of Alabama at Tuscaloosa and a member of the study team, said. "But searches for them in dwarf galaxies are much more challenging, and until now had failed."

To overcome the challenge of spotting black holes in merging dwarf galaxies, the team conducted a systematic survey of deep Chandra X-ray observations and compared them with optical and infrared data. Because the material around the black holes is heated to millions of degrees, it produces large amounts of high-energy light in the form of X-rays, which Chandra is adept at spotting. Hunting for pairs of bright X-ray sources in colliding dwarf galaxies, the researchers spotted two examples. The closest pair of colliding dwarf galaxy black holes, dubbed Mirabilis, is located 760 million light years from Earth in the galactic cluster Abell 133. These dwarf galaxies appear to be in the later stages of merging, with the tidal effects of the collision causing the formation of a long tail of material. The more distant merger is located around 3.2 billion light years away in the galactic cluster Abell 1758S and is in an earlier stage of collision.



SPACE SCIENCE

Discover intergalactic theories and understand the science of space

"The James Webb Space Telescope is a pathfinder of scientific discovery"

Rebecca Sohn

LAUNCH FOR THE MOON

NASA's biggest mission in over 50 years will put boots back on the Moon and bring us one step closer to Mars

Reported by Ailsa Harvey

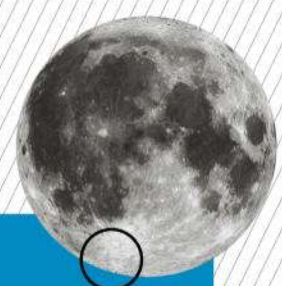
The Moon has captured the attention of humankind for as long as we have gazed upon the stars. Reflecting the Sun's light each dark night, its presence reminds us of worlds beyond our own. But astronauts have done much more than simply look upon it. On 20 July 1969 the first humans landed on the Moon. As part of a series of missions dubbed the Apollo program, NASA astronauts returned to Earth with more knowledge of the rocky orb than our species had ever acquired before. But to think that a handful of missions to this world would make us experts of this foreign terrain would be a mistake. We have only explored a tiny portion of the Moon, and there is still so much more to learn.

It's been half a century since we last visited the Moon, and NASA has made clear its plans to place the next astronauts on its surface by 2025. At least two more people will follow in the few dusty footsteps of the Apollo program's moonwalkers. When the Apollo program was launched, we knew few details about the silvery sphere that graces our skies. Upon the astronauts' successful return to Earth with samples from the Moon, we were able to learn the majority of what we know today about our planet's natural satellite. We learned that the surface of the Moon has a dust covering and the structure contains a core, mantle and crust just like Earth's. For Apollo, putting humans on the Moon was the main and final goal. It provided us with a better understanding of what was previously an uncharted and unimaginable environment. Soon this territory is to be further explored, and humanity's achievements in space travel will be expanded upon.

Apollo's successor is Artemis – a program aptly named after the Greek goddess of the Moon. Artemis is also the twin sister of Apollo. While the Apollo missions were executed solely by men, one prime goal of Artemis is to send the first woman to the Moon. In keeping with the theme, the vehicle that will carry the next astronauts to the Moon is a capsule called Orion, the name of the goddess Artemis' hunting partner. Sending a female astronaut to the farthest place humans have been from Earth will be an important step for the global space industry, and for equality.

Perhaps the most ambitious of the Artemis mission's objectives involves using the Moon

"We have only explored a tiny portion of the Moon, and there is still so much more to learn"



WHERE ARE WE GOING?

For the initial Artemis Moon missions, the selected astronauts will likely fly to the Moon's south pole. This area has great potential as it is believed to be home to the highest abundance of water ice. If we can extract this water, it could be used to sustain human exploration farther into space, whether that's as a human hydration source, rocket fuel resource or cooling system for equipment. Shackleton crater is a huge 19-kilometre (12-mile) depression in the Moon's surface and a feature well worth visiting. With a permanent shadow cast in the dips of the crater, the low temperatures make it a promising location for ice to form. In fact, these permanently lightless areas maintain some of the coldest temperatures in the entire Solar System. Although it's possible that water can be found even on the Moon's lit surfaces, an area likely to have the highest abundance of water is the best spot to start looking for further natural resources.

Shackleton crater is situated almost exactly at the Moon's south pole

THREE-PART PLAN

2022
Artemis I

The first mission will be uncrewed to test the safety of takeoff, the capsule's ability to orbit, descent and splashdown. The rocket will carry 13 small satellites into space to perform experiments and technology demonstrations. For six days the craft will orbit the Moon, collecting performance data.

2024
Artemis II

Carrying the first four Artemis astronauts, the Orion capsule will take the crew farther from Earth than humans have ever travelled before. Over the approximately ten-day mission, the crew will complete a lunar flyby and return to Earth, evaluating the spacecraft's systems while carrying humans.

2025
Artemis III

This will see the next man and first woman step onto the lunar surface. Providing previous missions have been successful, the astronauts will shoot towards the Moon, using the lunar lander to lower two people to the Moon's south polar region. They will remain on the Moon for around a week.

"The Moon is a stepping stone – in both time and distance – towards the Martian dream"

as a stepping stone for a mission to Mars. This is a planet that scientists believe could have once been home to life. Robots have done all the detective work on Mars so far, but NASA now aims to send astronauts there by the 2030s. With a future target set on the Red Planet, the return to the Moon will be used to provide us with the knowledge and tools to better navigate our Solar System.

But how can the Moon help prepare us for a mission to Mars, an entirely different and more unpredictable mission? Part of this logic is to maintain a gradual progression towards Mars, ensuring that astronauts are as experienced as they can be.

Humans have evolved to thrive on Earth, and they can't survive by themselves outside its atmosphere. In order to cheat nature and explore space, astronauts rely on science and technology, with NASA planning and preparing extensively. Much of what we know about how the human body reacts to low gravity, the hostility of outer space and how humans can survive in space comes from ongoing experiments on the International Space Station (ISS). Living 400 kilometres (248 miles) above our planet's surface is unimaginable to most of us, but a two-day journey to the ISS from Earth is nothing compared to the months it would take to travel to Mars. The Moon is a stepping stone – in both time and distance – towards the Martian dream.

The Artemis plans are well underway, and the first three missions are likely to be the catalyst for many more. Although NASA's sharpest minds will have the trip meticulously calculated, exactly what the astronauts will find remains to be seen. As the mission draws closer, a recent discovery has added significance to this ambitious plan. NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) discovered that the Moon has a higher abundance of water than previously anticipated and across a much greater area. The water was found on a sunlit surface of the Moon, meaning any available water isn't limited to the coldest, darkest regions and deep craters, as previously suggested. There could be more of this life-supporting resource trapped within the lunar surface for Artemis explorers to utilise. If this vital resource can be spotted using distant telescopes, time will only tell what we will learn when the Moon is back beneath our feet.

Astronauts will perform experiments and collect samples for return to Earth

Spacesuits have seen massive upgrades since the Apollo era

The Artemis I Flight Control Team simulating mission scenarios at Johnson Space Center

Ailsa Harvey
***How It Works* staff writer**
Ailsa writes for **How It Works** magazine, where she investigates topics in science, technology, history, space and the environment.

MAIN MISSION OBJECTIVES

Long-term presence
Following Apollo 17's three-day presence on the Moon, Artemis will send astronauts there for weeks.

Equality
A female astronaut hasn't set foot on the Moon yet. This mission will demonstrate the increasing role women have played in space missions since the Apollo era.

Partnerships
NASA has collaborated with private companies such as SpaceX and Boeing. These show space travel's shift towards commercialisation.

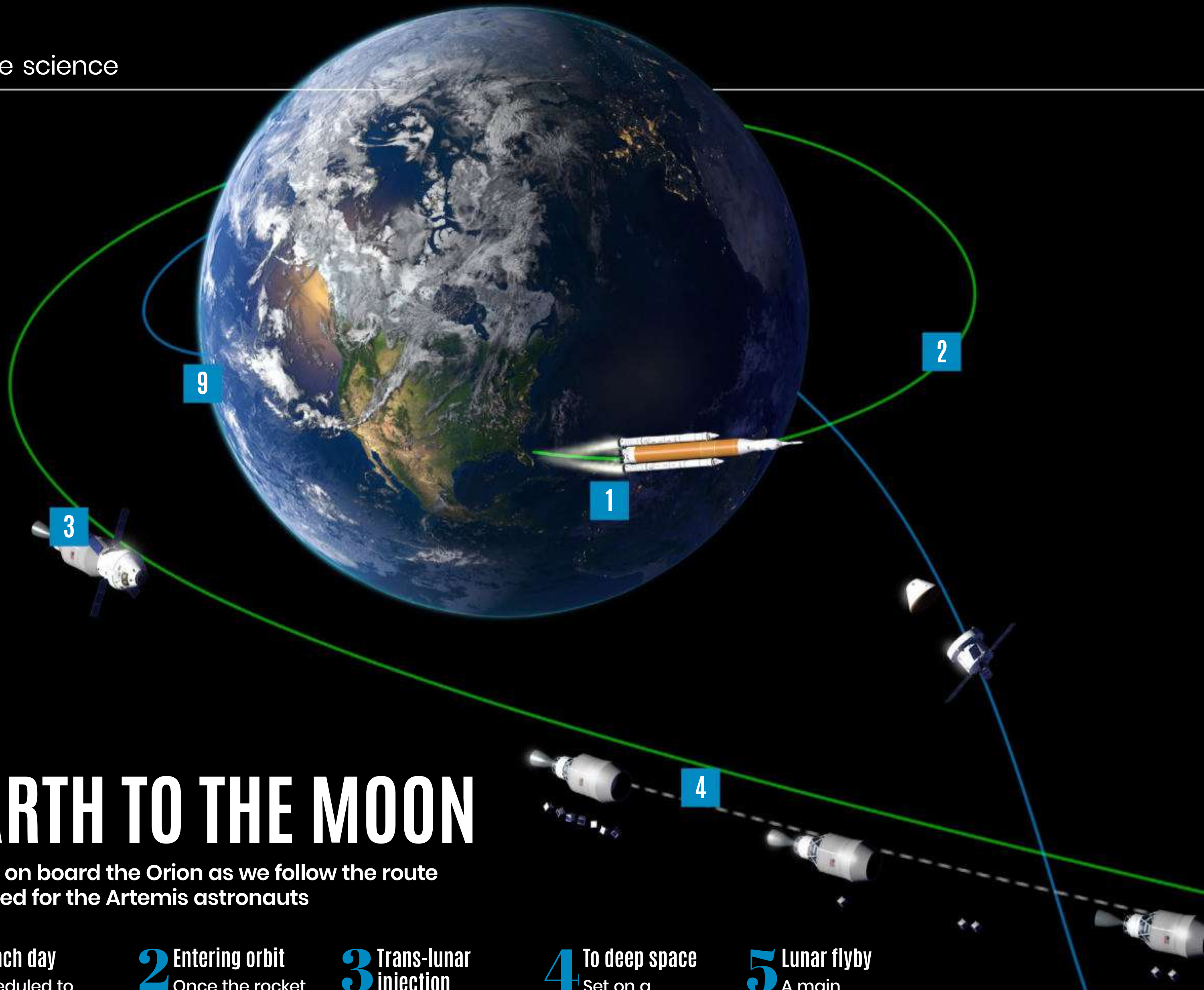
Technology
NASA is always learning from past missions; the spacecraft and spacesuits have been tailored to the Moon mission, exhibiting the latest in space technology.

Knowledge
Collecting further information about the lunar surface and deep space, NASA hopes to become better prepared for later missions back to the Moon and further afield.

Resources
Access to the lunar surface provides the opportunity to search for rare mineral deposits and exploit resources. Hydrogen and oxygen could be used as rocket fuel to travel from the Moon.

MOONWALKERS

If we want to send astronauts to the Moon, they will need the latest technology to assist them. While astronauts have undergone multiple spacewalks since the Apollo missions, these have not required them to walk on the surface of a celestial body. The next astronaut to walk on the Moon will do so in a brand-new, updated spacesuit. NASA has unveiled Artemis-generation spacesuits designed especially for the mission: one for the launch and landing, worn inside the spacecraft, and one to protect the bodies of those venturing outside the protection of the Orion capsule. The suits will be custom fit to their bodies, with the aim of improving upon the comfort and practicality of previous versions.



EARTH TO THE MOON

Jump on board the Orion as we follow the route planned for the Artemis astronauts

1 Launch day

Scheduled to launch in 2025, the third Artemis mission and second with crew on board launch from the Kennedy Space Center in Florida. All the action will be watched and monitored by the nearby Launch Control Center.

2 Entering orbit

Once the rocket has completed its task of taking Orion into orbit, its engines shut down and it will separate from the capsule. These rocket components then fall towards the Pacific Ocean. Left to fend for itself, Orion will deploy its solar arrays.

3 Trans-lunar injection

Having successfully made it into Earth orbit, the Orion vehicle is ready to cross over to the Moon. During a 20-minute burn, the engines fire to increase the speed of travel, displacing the spacecraft from its low-Earth orbit.

4 To deep space

Set on a carefully formulated trajectory, Orion will travel over 384,000 kilometres (239 miles). This needs to account for factors such as the pull of gravity and the movement of the Moon. Artemis I will be able to test the planned path.

5 Lunar flyby

A main engine burn 185 kilometres (115 miles) above the Moon's surface will put Orion on a trajectory to intercept the orbit of the planned Lunar Gateway space station, set to launch in November 2024.

6 Moon landing

Having docked with Gateway, the crew may need to inspect the station and collect any supplies they might need. While two astronauts will stay aboard the spacecraft in orbit, the other two will change over into a lander vehicle.

7 Spacewalk

The astronauts are likely to explore Shackleton crater, and will remain on the Moon for roughly seven days. As an area where water ice is present, they will explore the suitability of the lunar south pole for a permanent Moon base.

8 Ascent

Having carried out experiments on the Moon, the astronauts will reboard the Human Landing System and return to Gateway. Taking any essential samples back to Earth with them, they will return to Orion to make the journey back home.

9 Splashdown

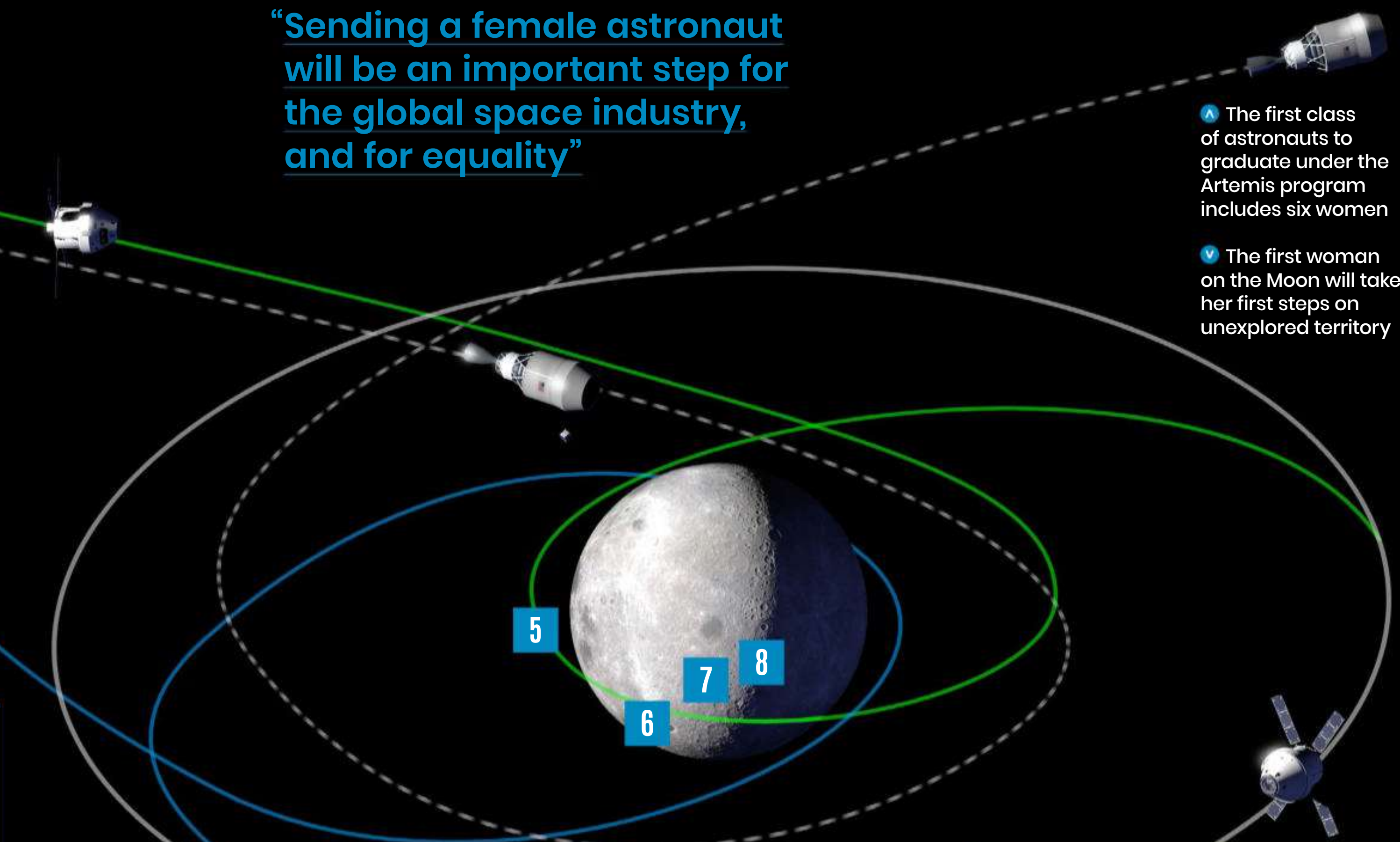
After less than 30 days in space, the parachuted capsule will land on Earth, its fall cushioned by the Pacific Ocean. NASA will have a team ready to retrieve the crew and the capsule.

FIRST WOMAN

Between 1969 and 1972, six missions took place in which 12 people walked on the surface of the Moon – all of them men. For such a high-risk mission, the most experienced astronauts were required, and at the time there were no women at NASA who had suitable test flight experience. For a long time space was viewed as an industry primarily for men, and it wasn't until 1978 that NASA selected its first female astronauts. As of March 2022, 75 women have been to space, and this mission will serve as a reminder of changing times.

While it's currently undecided who will be chosen, it will be one of NASA's astronauts who has already worked aboard the International Space Station. The team of astronauts is expected to be announced at least two years prior to the mission launch.

"Sending a female astronaut will be an important step for the global space industry, and for equality"



The first class of astronauts to graduate under the Artemis program includes six women

The first woman on the Moon will take her first steps on unexplored territory

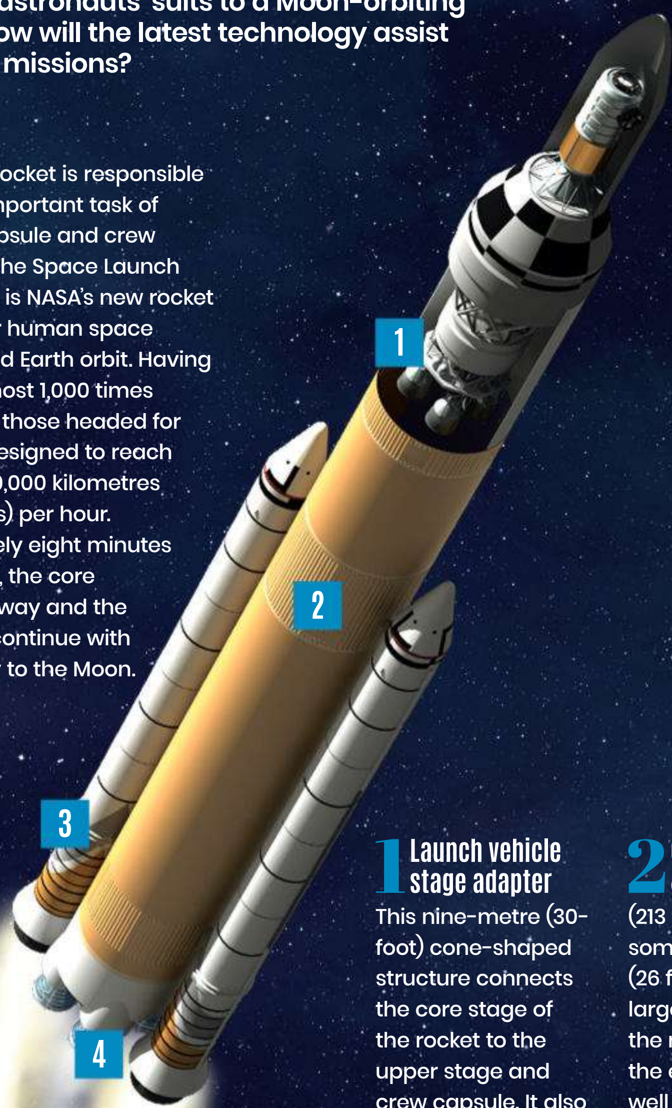
NASA testing exit procedures from an Orion spacecraft

TECH CHECK

From the astronauts' suits to a Moon-orbiting station, how will the latest technology assist the Moon missions?

Launch

The launch rocket is responsible for the all-important task of firing the capsule and crew into space. The Space Launch System (SLS) is NASA's new rocket designed for human space travel beyond Earth orbit. Having to travel almost 1,000 times farther than those headed for the ISS, it's designed to reach speeds of 40,000 kilometres (25,000 miles) per hour. Approximately eight minutes after launch, the core stage falls away and the astronauts continue with their journey to the Moon.



TRAVEL TECHNOLOGY

The Orion spacecraft that will deliver astronauts to the Moon is designed to have the lowest mass possible while still being strong enough to withstand the conditions of space. This will enable the capsule to carry the astronauts and their equipment using minimal fuel.

1 Launch vehicle stage adapter

This nine-metre (30-foot) cone-shaped structure connects the core stage of the rocket to the upper stage and crew capsule. It also acts as a protective shield for the engine in the upper stage.

2 Core stage

65 metres (213 feet) tall and some eight metres (26 feet) wide, the largest area of the rocket stores the engine fuel as well as the flight computers needed to control the rocket.

3 Solid rocket booster

These provide 75 per cent of the rocket's thrust during launch. After the initial ascent, the boosters separate from the SLS and fall back to Earth.

4 RS-25 engines

Liquid hydrogen and liquid oxygen-fuelled engines are evenly distributed in a square pattern to add stability, as they produce nearly 9 million newtons of force. It takes five seconds for the engines to reach 100 per cent power.

5 Crew module

The astronauts' capsule is situated near the top of the rocket, allowing modules to safely detach below them.

6 Launch abort system

Coming into play if a problem arises, the top of the rocket has a motor that will pull the Orion spacecraft away from the rest of the rocket for a safe landing.

"For Apollo, putting humans on the Moon was the main and final goal"

GATEWAY TO THE MOON

For exploration of another celestial body, astronauts need a base camp. The Lunar Gateway will serve this purpose. Orbiting the Moon, Orion will synchronise with the path of this station. When the spacecraft reaches Gateway it will dock, and then the astronauts can leave Orion. Serving a similar purpose to the ISS – but travelling in a completely different orbit around the Moon – Gateway is a place where astronauts can conduct science experiments and prepare for the main stage of their mission, the landing. Unlike the ISS, however, the Lunar Gateway will house astronauts for shorter periods and won't be permanently occupied. Built with return trips to the Moon beyond the initial Artemis missions and long-term human presence in mind, this component will become vital for deep-space exploration.

This shows how the Orion spacecraft will dock with the Lunar Gateway

MOON LANDING

Transporting the astronauts to their lunar destination is the SpaceX Starship Human Landing System. This vehicle is designed with a pressurised crew cabin for its passengers to dwell inside before stepping out onto the surface of the Moon. Other companies working on lunar landers include Blue Origin, Boeing and Dynetics. To safely make it onto the lunar surface, the vehicle will need to achieve a slow soft landing.

Q&A
STEVEN SWANSON

The three-time NASA astronaut tells us about life in space and the significance of Artemis

During his career at NASA, Swanson logged over 195 days in space, undertaking five spacewalks. His three missions to the ISS include two Space Shuttle flights (STS-117 and STS-119) and one Soyuz flight (TMA-12M).

How does NASA select astronauts?
Nobody knows for sure. Really it's up to the chief of the astronaut office to make that selection, and sometimes others depending on how high profile the mission is. But it's partly just where you are in the queue, because we come in as a group together. The people who came in the group before will fly before you do. I didn't think about an astronaut career until I was about 25. It took 12 years from that point to become one, and I ended up working 11 of those years at NASA as an engineer.

What's it like to spend significant time away from Earth?
I spent about six months in space, and it's not tremendously difficult. Family and friends is the first thing you miss, but we could Skype and the communication with our families was good. You can get down periods when you get a little tired of it – you haven't really gone outside and the food gets old after a while.

How much have the spacesuits improved for Artemis?
The biggest difference is in the shoulders. You get the ability to really reach around and have more movement, like you would without a suit on. They also have better mobility on the legs. On the International Space Station you didn't really use your legs much for anything, so it didn't matter how much mobility you had in your lower body. Now it's going to matter tremendously on the Moon, so they've modified the lower part to be more moveable.

What changes can the Artemis crew expect in their bodies?
The first thing we have to worry about is muscle and bone loss. Astronauts now work out two hours a day, so we do a pretty good job of mitigating that, but we still see some muscle loss. Bone loss is pretty much covered now. I only had one per cent bone loss from six months on board, and that was a good number. That comes back after about a year.

In our experiments while we were up there, we found that 30 to 40 per cent of the astronauts are getting major changes in their vision, and we haven't figured out exactly why. That's an ongoing process right now. There's just many things that change while you're up there. We've known for a while that the immune system gets degraded, so we're very careful about being quarantined before we go so nobody takes any germs or bugs with them on the way up. You don't want to get sick up there.

How significant do you think the Artemis program is?
The real goal is Mars. And we will use the Moon as a testbed because Mars is a very difficult mission. It's going to take almost three years, and you can't come home early on a Mars mission. It's a seven or eight-month journey to get there and you have to wait 15 months there for the planets to align correctly again before you return. It has to be very well thought out, and the best way to do that is on the Moon. As well as Mars, we can also use the Moon as a testbed for other things – to see how we can actually gather materials from the Moon itself and maybe use that to make our fuel.

© NASA

Swanson was selected as a NASA astronaut in 1998

Swanson (left) prepares for the Soyuz TMA-12M launch with Aleksandr Skvortsov (middle) and Oleg Artemyev (right)

FOCUS ON

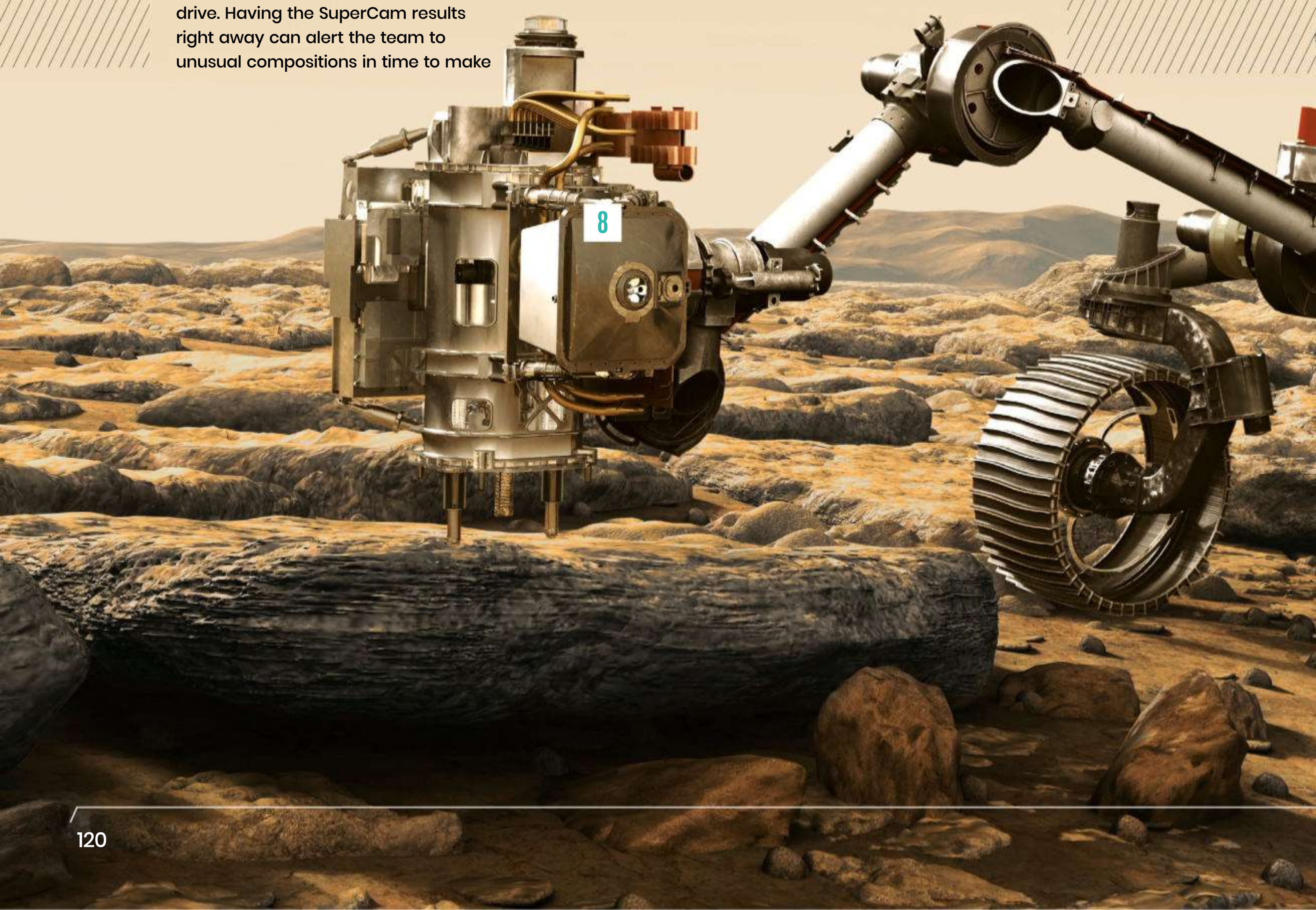
MARS ROVER PICKS ITS OWN ROCK SAMPLES

Perseverance is analysing each sample's elemental composition in the ongoing search for ancient life

Reported by Elizabeth Howell

NASA is hailing the Perseverance rover's improved ability to pick its own targets as a way of speeding up science on Mars. Without explicit direction from Earth, the Perseverance rover zapped two rock targets with its SuperCam instrument on Sol 442 (18 May 2022) to learn more about their elemental compositions, mission scientists said in an update on 31 May. "Normally when the rover team picks the targets, observations aren't made until the following day," Roger Wiens, principal investigator of SuperCam and a planetary scientist at Los Alamos National Laboratory, said. "If Perseverance picks its own targets, it can shoot them right after a drive. Having the SuperCam results right away can alert the team to unusual compositions in time to make decisions about further analyses before the rover moves on," Wiens added.

Perseverance's software for target selection is called Autonomous Exploration for Gathering Increased Science (AEGIS) and was developed at NASA's Jet Propulsion Laboratory in California for other rover missions. The software was then adapted for Perseverance's SuperCam instrument. "AEGIS requests Navigation Camera (Navcam) images to be taken, and it then analyses the images to find rocks and

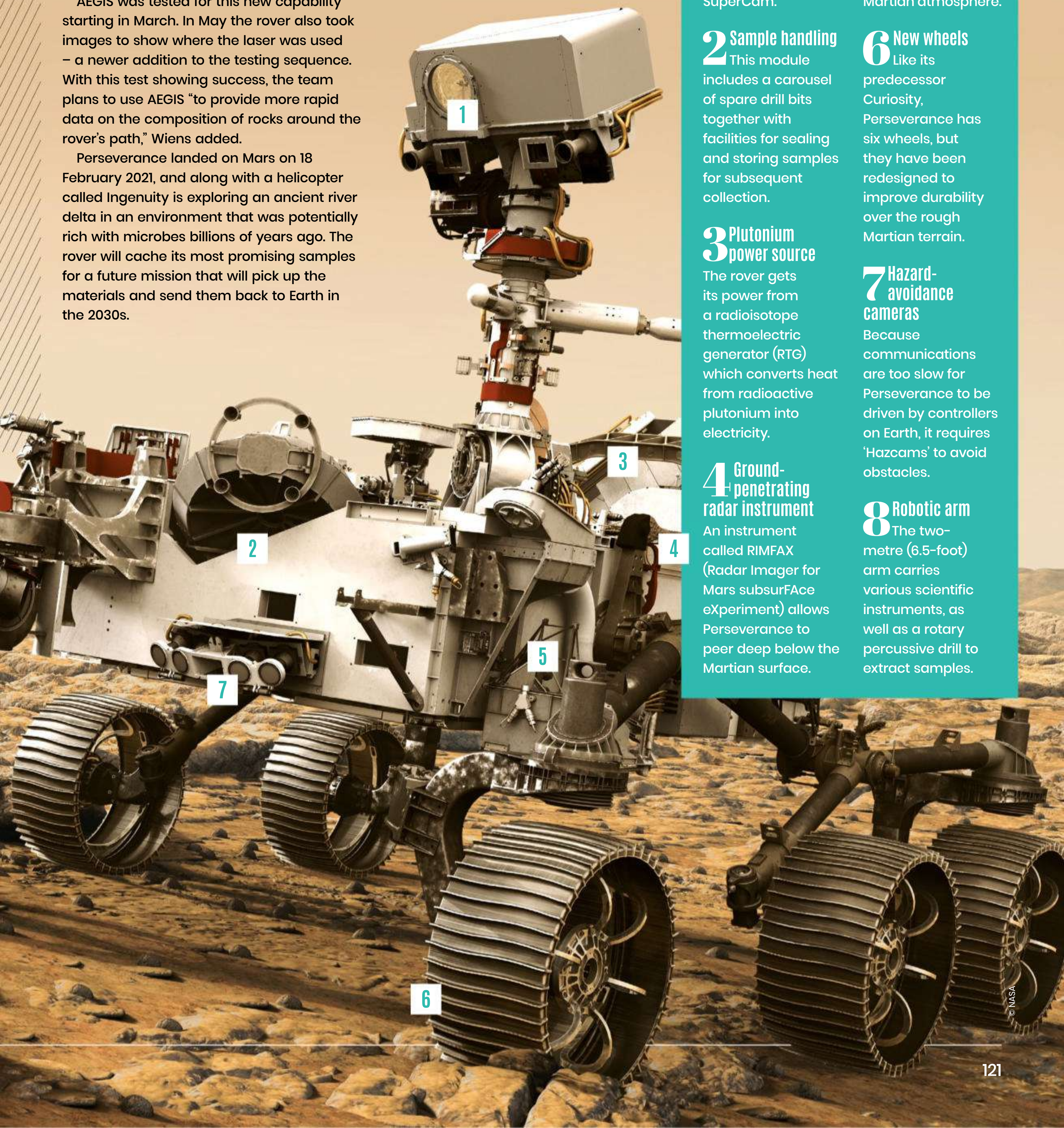


prioritise them for analysis based on size, brightness and several other features," Wiens said. "It subsequently initiates a sequence in which SuperCam fires its laser to determine the chemical make-up of one or two top-priority targets selected from Navcam images."

AEGIS was tested for this new capability starting in March. In May the rover also took images to show where the laser was used – a newer addition to the testing sequence. With this test showing success, the team plans to use AEGIS "to provide more rapid data on the composition of rocks around the rover's path," Wiens added.

Perseverance landed on Mars on 18 February 2021, and along with a helicopter called Ingenuity is exploring an ancient river delta in an environment that was potentially rich with microbes billions of years ago. The rover will cache its most promising samples for a future mission that will pick up the materials and send them back to Earth in the 2030s.

> **"It analyses images to find rocks and prioritise them for analysis based on size, brightness and several other features"** **Roger Wiens**



1 Camera mast The mast carries an array of cameras, some for navigation and some for scientific analysis, including the laser-firing SuperCam.

2 Sample handling This module includes a carousel of spare drill bits together with facilities for sealing and storing samples for subsequent collection.

3 Plutonium power source The rover gets its power from a radioisotope thermoelectric generator (RTG) which converts heat from radioactive plutonium into electricity.

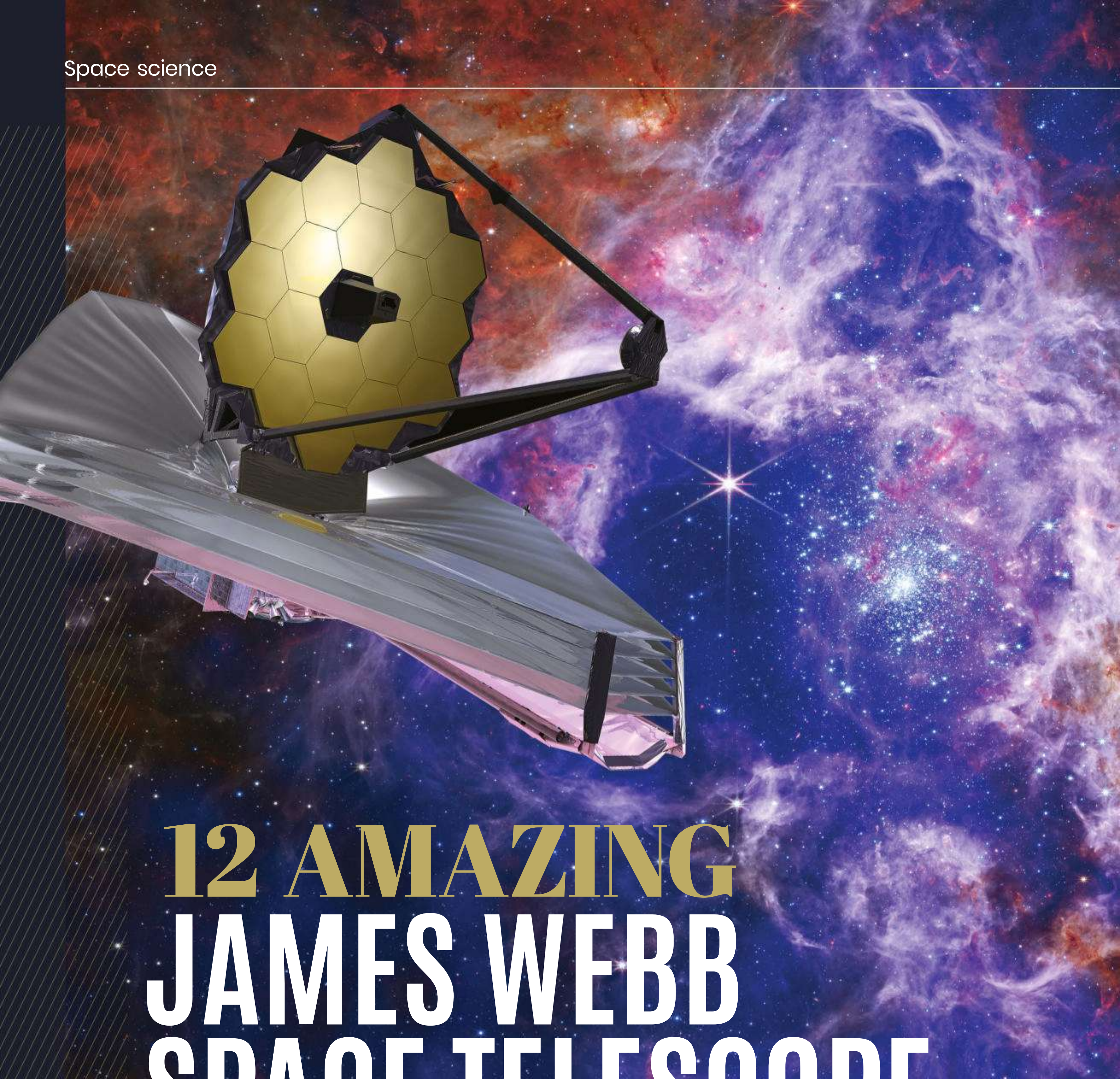
4 Ground-penetrating radar instrument An instrument called RIMFAX (Radar Imager for Mars subsurFAce eXperiment) allows Perseverance to peer deep below the Martian surface.

5 MOXIE The Mars OXygen In-situ resource utilization Experiment is testing a method for producing oxygen from CO_2 in the Martian atmosphere.

6 New wheels Like its predecessor Curiosity, Perseverance has six wheels, but they have been redesigned to improve durability over the rough Martian terrain.

7 Hazard-avoidance cameras Because communications are too slow for Perseverance to be driven by controllers on Earth, it requires 'Hazcams' to avoid obstacles.

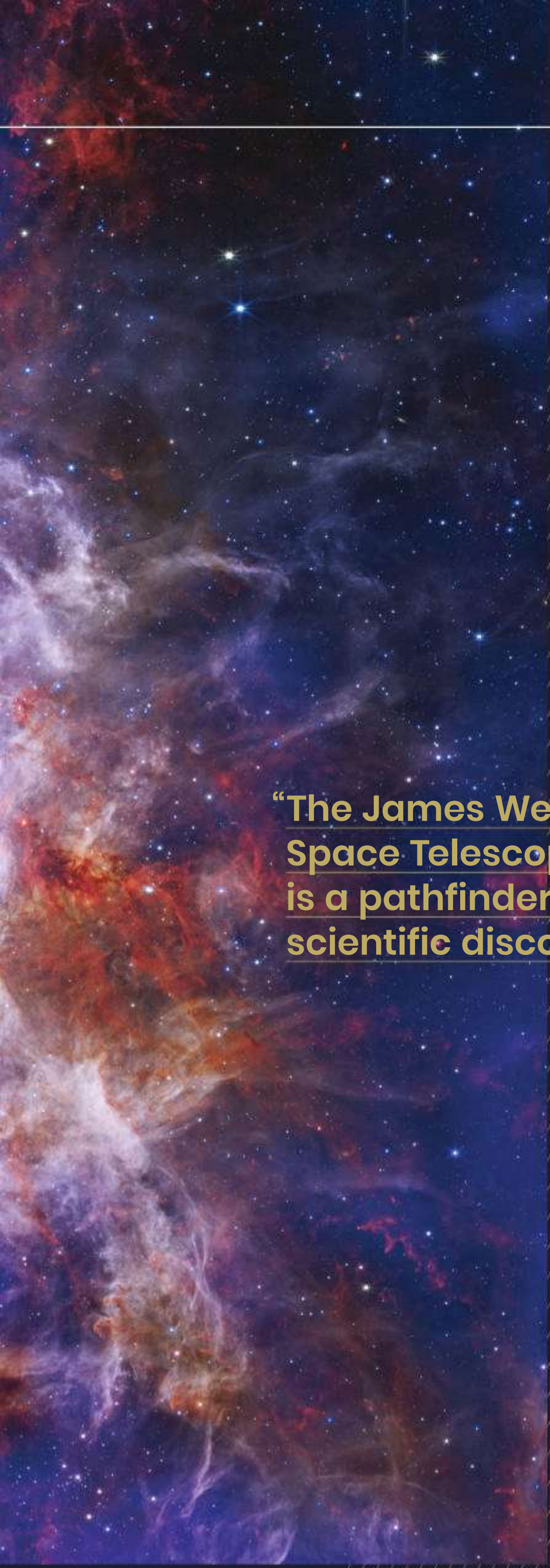
8 Robotic arm The two-metre (6.5-foot) arm carries various scientific instruments, as well as a rotary percussive drill to extract samples.



12 AMAZING JAMES WEBB SPACE TELESCOPE BREAKTHROUGHS

Webb is peering across the universe to discover new things about planets, galaxies and other cosmic objects

Written by Rebecca Sohn



"The James Webb Space Telescope is a pathfinder of scientific discovery"

NASA's deep-space observing telescope is looking at the universe like never before. The James Webb Space Telescope is a pathfinder of scientific discovery, generating incredible insights about galaxies, planets, stars and all sorts of interesting cosmic objects. The telescope is near the beginning of its cosmic journey, as it is rated for 20 years of operations and just launched in December 2021. Billed as a successor to the venerable Hubble Space Telescope, Webb is also breaking ground in science excitement.

1 WEBB IS HAILED AS THE GREATEST SPACE BREAKTHROUGH

When Webb launched on 25 December 2021, it was the culmination of decades of work by NASA scientists and engineers. The launch went off without a hitch, as did the numerous steps of the telescope's deployment in the following months. In mid-July Webb released its stunning first images. The infrared telescope will help us see almost every part of our universe in greater detail, including the most distant galaxies, allowing us a glimpse into the past. "Within days of [Webb] coming online in late June 2022, researchers began discovering thousands of new galaxies more distant and ancient than any previously documented – some perhaps more than 150 million years older than the oldest identified by Hubble," editors of the journal *Science* said. The journal named Webb as its Science Breakthrough of 2022, while the journal *Nature* chose Jane Rigby, Webb's operations project scientist, to include in their 'ten people who helped shape science stories' list for 2022.

"What's more, the telescope is capable of collecting enough light from astronomical objects – ranging from birthing stars to exoplanets – to reveal what they are made of and how they are moving through space," the editors of *Science* said. "This data has already begun to reveal the atmospheric composition of planets hundreds of light years from Earth in great detail, offering hints as to their ability to potentially support life as we know it."

Webb is a worthy successor to Hubble, spying further into the universe

2 STARS BORN IN THE PILLARS OF CREATION

The Pillars of Creation in the Eagle Nebula have long been one of the Hubble Space Telescope's most iconic images. But though the telescope, which detects mostly visible light, captured the structure's impressive clouds, the 'creation' happening within them was hidden. Now, Webb's infrared imaging has managed to capture it in the form of numerous protostars. Appearing as tiny red dots against the smoky backdrop of the pillars, these collections of dust and gas, each many times larger than our Solar System, are stars being born. "These young stars that we see in the image are not yet burning hydrogen," Derek Ward-Thompson, head of the school of natural sciences at the University of Central Lancashire in the UK, said. "But gradually, as more and more material falls in, the middle becomes denser and denser, and then suddenly it becomes so dense that the hydrogen burning switches on, and then suddenly their temperature jumps up to about 2 million degrees Celsius [3.5 million degrees Fahrenheit]." The image was created using different colours to represent mostly invisible infrared wavelengths, said Anton Koekemoer, a research astronomer at the Space Telescope Science Institute in Baltimore, who put the image together using Webb data.

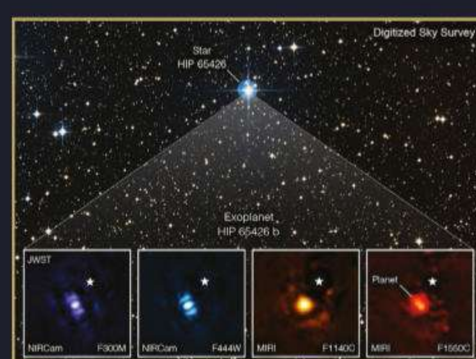
▲ The Pillars of Creation are iconic in astronomy

▸ HIP 65426 b was once known as Najsakopajk

3 WEBB'S FIRST DIRECT IMAGE OF AN EXOPLANET

Scientists discovered the first exoplanets in the 1990s, and today there are over 3,000 known worlds orbiting faraway stars. Still, only around two dozen of these have been imaged directly. Most exoplanets are so far away that they can only be detected through a dip in the light of the star they're orbiting when that planet passes in front of its host star. But Webb could change that. In September 2022, it captured its first direct image of an exoplanet. "This is a transformative moment, not only for Webb but also for astronomy generally," Sasha Hinkley, an astronomer at the University of Exeter in the UK who led these observations, said.

The planet, called HIP 65426 b, was discovered in 2017. To view it, scientists used two of Webb's cameras, several filters and the telescope's coronagraphs – tools which block out the light of the central star. Along with the telescope's exceptional sensitivity, the planet has several features that make it easier to observe. At 100 times the distance from our Sun to Earth, this planet is much farther away from its host star than any planet in our Solar System – in contrast, Pluto is only 40 times that Sun-Earth distance. A colossal gas giant, it's also exceptionally large – about 12 times the size of Jupiter.



> "These young stars that we see in the image are not yet burning hydrogen"
> **Derek Ward-Thompson**

4 RE-IMAGING THE PHANTOM GALAXY

Though the Phantom Galaxy is difficult to find in the night sky, its brilliance is far from invisible, especially when captured in infrared. Hubble's optical image of the galaxy shows the galaxy's perfect spiral structure and its distribution of stars, in arms extending outwards from a radiant centre. But a new Webb image reveals fibre-like structures of heat-emitting dust and gas emanating from a bright centre rendered in vivid electric blue. The image will shed light on star-forming regions scattered in the galaxy's spiral arms. A mesmerising composite image combining the Hubble Space Telescope and Webb images features aspects of both optical and infrared observations of the galaxy.

5 MYSTERIOUS BOXY RIPPLES EXIST AROUND A WOLF-RAYET STAR

In July 2022, Webb captured an image of a distant star that featured Webb's signature diffraction pattern. But around the star, called WR 140, is a pattern that looks equally unreal – a ripple-like pattern of concentric rings that have a peculiar, slightly boxy shape. Unlike the diffraction pattern, the unlikely shaped rings are real features. "The six-pointed blue structure is an artefact due to optical diffraction from the bright star WR 140 in this JWST MIRI image," wrote Mark McCaughrean, an interdisciplinary scientist in the James Webb Space Telescope science working group and a science advisor to the European Space Agency, in a twitter thread. "But the red curvy-yet-boxy stuff is real, a series of shells around WR 140. Actually in space. Around a star."

Wolf-Rayet stars are massive stars near the end of their lives, already having released much of their hydrogen. The strangely shaped rings are caused by the interaction between WR 140 and its smaller companion star. The stars are surrounded by a cloud of dust that is sculpted into that shape by its companion star, said McCaughrean. Ryan Lau, an astronomer at NOIRlab in Arizona, led the team studying these observations as part of the JWST Early Release Science program. In October, the team published a study on the observations in the journal *Nature Astronomy*.

Ⓐ The Phantom Galaxy is also called Messier 74

Ⓐ Wolf-Rayet stars are rather rare

"These [galaxies] are well beyond what we could have imagined finding before Webb"

Brant Robertson

6 FINDING THE MOST DISTANT GALAXIES EVER

Webb was made to observe the most distant galaxies in the universe, and in mid-December 2022, scientists confirmed that they had done just that. The telescope has officially observed the four most distant galaxies known, which also means they are the oldest. Webb observed the galaxies as they appeared about 13.4 billion years ago, when the universe was only 350 million years old, about two per cent of its current age.

Scientists suspected that the four galaxies were incredibly ancient, like hundreds of others identified by Webb. As part of the JWST Advanced Deep Extragalactic Survey (JADES), researchers confirmed their age, analysing data from the telescope's Near Infrared Spectrograph to find out how fast the galaxies were moving away from the telescope. This is the galaxies' redshift – how much the wavelengths of light they shed have lengthened as the universe expands. Their redshift was 13.2, the highest ever measured. "These [galaxies] are well beyond what we could have imagined finding before Webb," Brant Robertson, an astrophysicist at the University California, Santa Cruz, and one of the researchers involved in the observations, said. "With Webb, for the first time we can now find such distant galaxies and then confirm spectroscopically that they really are that far away."

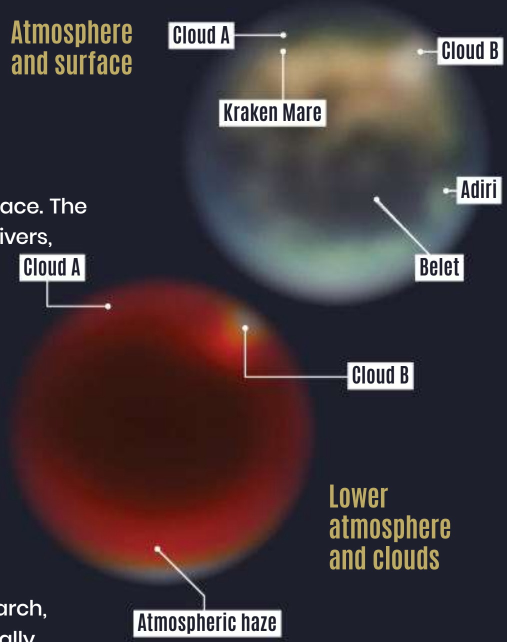
A Webb can peer back into the ancient universe with its high-tech infrared instruments

B WASP-39 b is classified as a 'hot Jupiter'

7 LOOKING AT AN EXOPLANET'S ATMOSPHERE IN DETAIL

Thanks to Webb, a planet orbiting a star in the constellation of Virgo is now the most explored world outside our Solar System. The planet is called WASP-39 b and is about 700 light years from Earth. It's a boiling gas giant about the size of Saturn, orbiting its host star at an absurdly close distance – about eight times closer to its host star than the planet Mercury is to our Sun. Using Webb's main camera and two of its spectrographs, scientists identified carbon dioxide in its atmosphere – the first time the gas has ever been found in an exoplanet's atmosphere – though the planet's bulky atmosphere is dominated by thick clouds containing sulphur and silicates, including sulphur dioxide.

8 GLIMPSING TITAN'S CLOUDS



Saturn's moon Titan is a weird and intriguing place. The moon has 'rock' made of water ice, as well as rivers, lakes and seas made of liquid methane and ethane. It's also the only moon in our Solar System to have a thick atmosphere – a hazy one dotted with methane clouds. Scientists got a glimpse of some of those clouds in November 2022, when Webb captured atmospheric data from the weird moon.

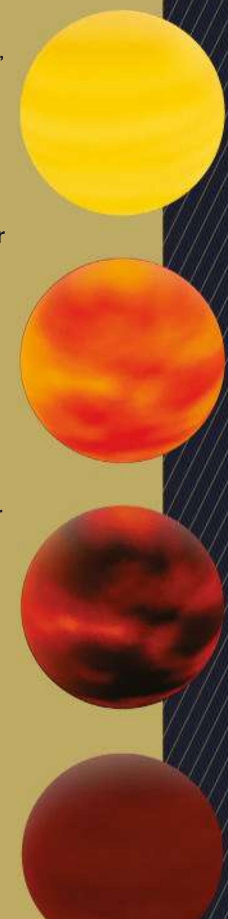
Researchers studying Titan with Webb expressed their excitement on receiving the data. "At first glance, it's simply extraordinary," Sébastien Rodriguez, an astronomer at the Université Paris Cité and colleague on the research, said. "I think we're seeing a cloud!" They eventually found that the telescope captured not one but two clouds, including one over the moon's largest sea, Kraken Mare. The team was so intrigued that they contacted Keck Observatory in Hawaii, which was able to observe Titan just two days later. In the Keck observations there's a cloud over Kraken Mare in the same place, though it's a different shape, indicating that the cloud either changed or another cloud moved into the same spot.

9 THE SECRETS OF THE SOUTHERN RING NEBULA

Scientists always thought of the Southern Ring Nebula as rather unremarkable. The thinking went that the nebula was simply a dying star, called a white dwarf, that had expelled its outer layers, which glow brightly as the white dwarf radiates waves of energy. Scientists also knew that another non-dying star, part of a binary system, was largely obscured beneath the brightly lit gas. But Webb's stunning image of the nebula, released as part of its first images and data, made it clear that it wasn't that simple. Webb imaged the cloud with two of its instruments, the Near Infrared Camera (NIRCam) and the Mid-Infrared Instrument (MIRI). With MIRI, researchers saw that the white dwarf wasn't invisible, as they'd expected in that wavelength, but glowing red, surrounded by a haze of cool gas. Where did the gas come from? The only logical explanation, it seemed, was that the nebula hid a third star, which was the source of the gas. The telescope's main camera also captured intriguing shells around the outer edges of the nebula, somewhat like those around WR 140. They think a third star, somewhere between the two known ones, could have caused the ripple-like shells.

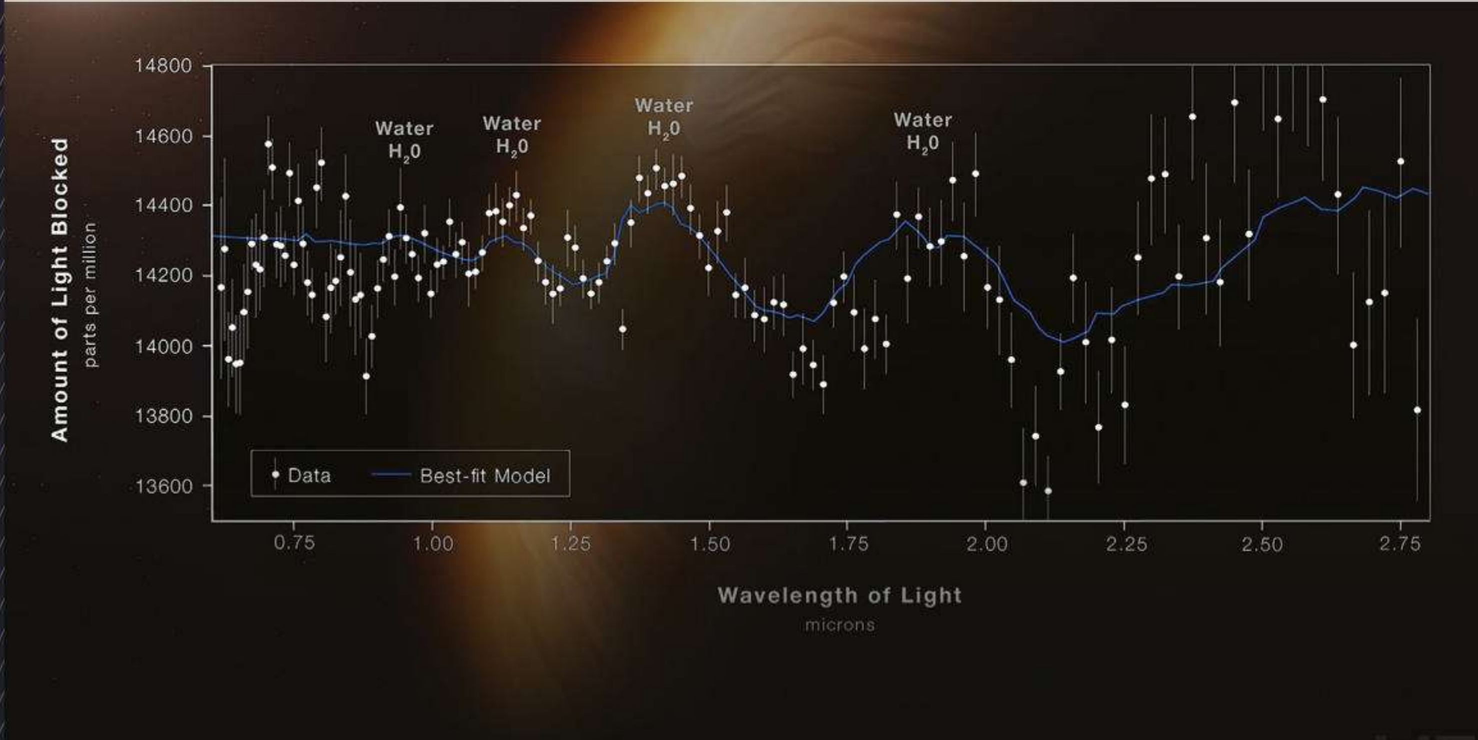
NGC 3132, the Southern Ring Nebula, is in the constellation of Vela

10 WEBB DISCOVERS A BROWN DWARF WITH SAND CLOUDS



Though many telescopes have identified exoplanets, Webb wasn't designed to. But discover one it did – and it's an exceptionally weird one. For one, VHS 1256 b isn't a planet at all. It's a brown dwarf – bigger than a planet, but too small to be a proper star. This one gives off a dim, reddish glow, a product of the modified form of fusion that happens on objects that are very massive, but are too small to fuse hydrogen. Stranger still, Webb observed that the brown dwarf has sandy silicate clouds – a first for this kind of object. The exoplanet is also small for a brown dwarf, and therefore young.

As with WASP-39 b, Webb was able to identify individual chemicals in the brown dwarf's strange atmosphere, such as water, methane, carbon dioxide and potassium, among others. Ratios of the different compounds suggest that the object has a turbulent atmosphere. "In a calm atmosphere, there's an expected ratio of, say, methane and carbon monoxide," Sasha Hinkley, an astronomer at the University of Exeter in the UK and one of the study's co-authors, said. "But in many exoplanet atmospheres we're finding that this ratio is very skewed, suggesting that there is turbulent vertical mixing in these atmospheres, dredging up carbon dioxide from deep down to mix with the methane higher up in the atmosphere."



11 NOT-SO-CLOUDLESS PLANET

As part of its first release of Webb data, NASA released the telescope's first spectrum of the atmosphere of an exoplanet, from a planet called WASP-96 b. Webb's spectrographs analysed the light of the planet's star filtered through the planet's atmosphere as it crossed in front, obtaining a spectrum, a kind of 'barcode' of the wavelengths of light absorbed by the planet's atmosphere. The spectrum detected signs of hazy skies, clouds and water vapour on the planet. This is strange, considering that scientists previously thought the planet didn't have any clouds at all.

The planet's atmosphere has a strong sodium signature, something that researchers thought until recently meant it had unique, entirely cloudless skies. The results are so contradictory that scientists are reanalysing the Webb and previous data, trying to figure out how to reconcile the seemingly opposite conclusions.

The signs of water on the distant planet almost definitely don't indicate that it could have life. The planet is a 'hot Jupiter' – a gas giant half as massive but slightly larger than our Solar System's largest planet. It's very close to its host star, orbiting it every 3.4 days.

WASP-96 b is unlike any planet in the Solar System

Webb unveiled intense star formation in colliding galaxies

12 HIDDEN STAR FORMATION AS GALAXIES COLLIDE

One of Webb's strengths as an infrared telescope is its ability to peer through dust, revealing things hidden from telescopes like Hubble, which use mostly visible light. When Webb captured an image of two galaxies colliding, it saw something Hubble had missed – an area of intense star formation, which scientists say is producing stars 20 times faster than in our own galaxy. In the new image, the merging galaxies, called IC 1623, contain an area of star formation that shines so bright with infrared radiation that it produces Webb's typical pointed-star diffraction pattern, which is usually the result of its observing bright stars. The area makes up a completely new layer of the image, hidden from Hubble.

FOCUS ON

JAMES WEBB SPACE TELESCOPE FINDS A GARGANTUAN GEYSER ON SATURN'S MOON

Scientists are longing to go back to the moon to sample the plume material for signs of life

Reported by Isobel Whitcomb

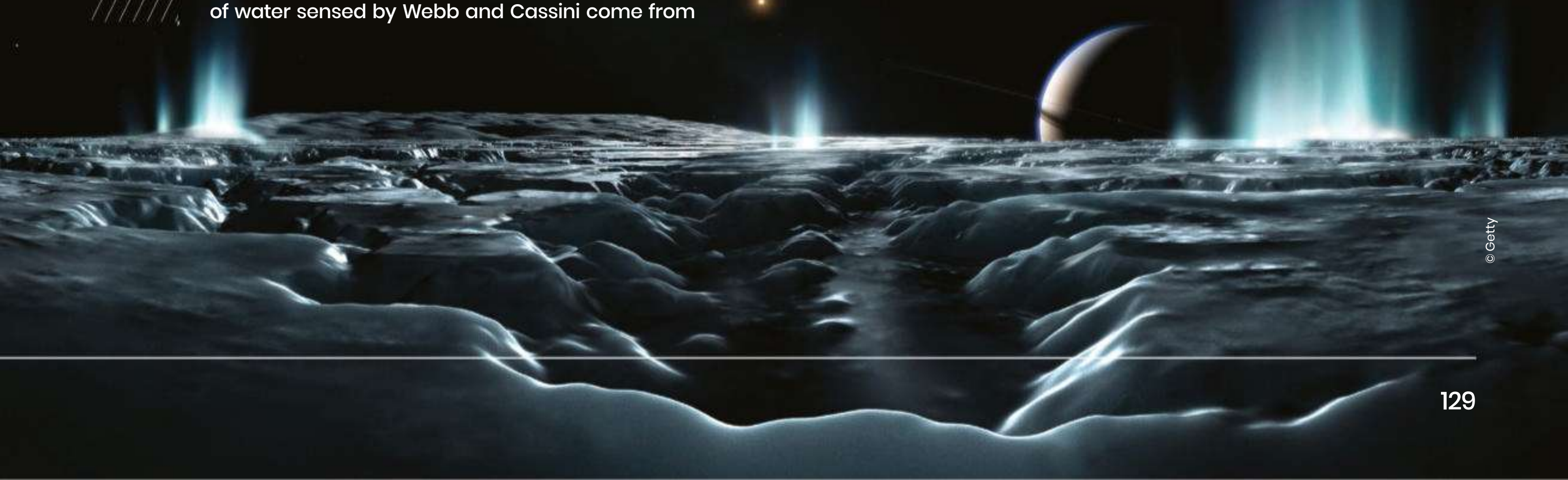
Scientists caught Saturn's icy moon Enceladus spraying a huge plume of watery vapour far into space – and that plume likely contains many of the chemical ingredients for life. "It's immense," Sara Faggi, a planetary astronomer at NASA's Goddard Space Flight Center, said. This isn't the first time scientists have seen Enceladus spout water, but the new telescope's wider perspective and higher sensitivity showed that the jets of vapour shoot much farther into space than previously realised.

Scientists first learned of Enceladus' watery blasts in 2005, when NASA's Cassini spacecraft caught icy particles shooting up through large lunar cracks called 'tiger stripes'. Analysis revealed that the jets contained methane, carbon dioxide and ammonia – organic molecules containing the chemical building blocks necessary for the development of life. It's even possible that some of these gases were produced by life itself, burping out methane deep beneath the surface of Enceladus.

Water is another piece of evidence in the case for possible life on Enceladus. Enceladus is totally encrusted in a thick layer of water ice, but measurements of the moon's rotation suggest that a vast ocean is hidden beneath that frozen crust. Scientists think the spurts of water sensed by Webb and Cassini come from hydrothermal vents in the ocean floor – a hypothesis supported by the presence of silica, a common ingredient in planetary crusts, in the vapour plumes.

NASA scientists are discussing future return missions to seek out signs of life on Enceladus. The proposed Enceladus Orbilander would orbit the moon for about six months, flying through its watery plumes and collecting samples. Then the spacecraft would convert into a lander, descending on the surface of the icy moon. Orbilander would carry instruments to weigh and analyse molecules, as well as a DNA sequencer and a microscope. Cameras, radio sounders and lasers would remotely scan the moon's surface.

Another proposed mission involves sending an autonomous 'snake robot' into the watery depths below Enceladus' surface. The robot, dubbed the Exobiology Extant Life Surveyor, features cameras and lidar on its head to help it navigate the unknown environment of Enceladus' ocean floor.



An artist's impression of plumes on Enceladus

© Getty

TEN AMAZING SPACE STATION EXPERIMENTS

The International Space Station is more than just an outpost in space – it's a huge orbiting research laboratory

Interviewed by Laura Mears

The International Space Station (ISS) houses an incredible array of cutting-edge research facilities, allowing scientists back on Earth to conduct pioneering experiments in space. Different space agencies, academic institutions and private companies from across the world share the onboard facilities, taking it in turns to perform their experiments. Delicate tests can be conducted in microgravity inside the station itself, and outside experiments can be exposed to vacuum and radiation. With a clear view of space and out of the reaches of Earth's atmosphere, the ISS is also the perfect place to investigate the universe.

Some experiments investigate the physical sciences, looking at the behaviour of different materials in space, while others focus on biology, helping us understand how the human body is affected by space travel or how to grow food away from Earth. Others monitor Earth, taking advantage of the ISS' incredible view of our planet below.

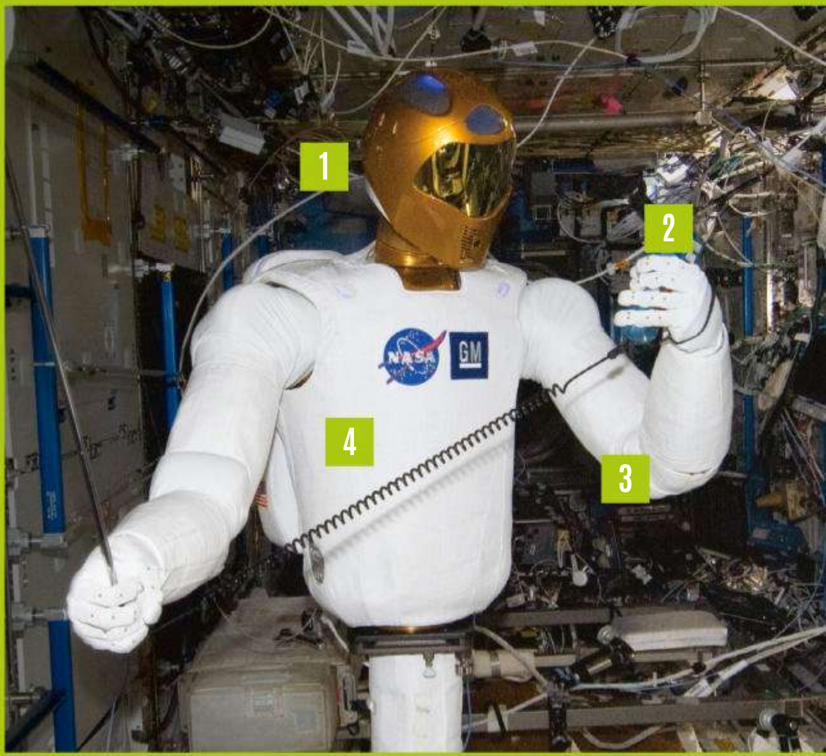
The station also houses sophisticated equipment to examine space itself, and inside, advanced technology can be developed and tested in microgravity. Join us as we investigate ten awesome International Space Station experiments, from robotic crew members to an orbiting coffee machine.

ONE
WORKING WITH A HUMANOID

The ISS is always occupied by at least three human crew members, and since February 2011 they've been joined by Robonaut 2. On its arrival, the robotic crew member met the ISS commander with a handshake and greeted the public by signing 'hello world'. This incredible robot is the result of a collaboration between NASA, General Motors and Oceaneering Space Systems. Together they wanted to create a robot that was capable of carrying out repetitive, uncomfortable or dangerous tasks.

Robonaut 2's hands are flexible like our own – its thumb can bend to touch all of its fingers – and it has a grip strength equivalent to a human hand. Its arms are soft and padded and contain springs that give way easily when pushed, allowing astronauts to work safely alongside Robonaut 2.

The robot has infrared cameras for depth perception and an additional four visible-light cameras that help it 'see' in stereo. Since 2014, it also has a pair of flexible legs, each fitted with an 'end effector' where the foot should be, allowing it to move freely around the station. With a little more upgrading, the team hope that this robotic crewmate will eventually be able to work on the outside of the ISS.



1 Human-like senses
Robonaut 2 has over 350 sensors, including five cameras in its helmet.

2 Opposable thumbs
Robonaut 2 has flexible hands, and can easily touch its little finger to its thumb.

3 Padded metal
The robot is made from aluminium and steel, but is coated in soft protective padding.

4 Robonaut's brain
The 38 processors responsible for controlling it are housed inside its torso.

TWO
SQUID BEHAVIOUR IN MICROGRAVITY

The final flight of NASA's Space Shuttle program carried some unusual passengers to the ISS: three Hawaiian bobtail squid. These little sea creatures are usually found hiding in the sand on shallow seabeds, and at only five centimetres (two inches) long, they're the perfect size for experiments.

This species was chosen because of its close relationship with another organism. Hawaiian bobtail squid naturally share their bodies with a species of bacteria called *Vibrio fischeri*. These bioluminescent microbes light the squid's silhouette, helping keep it camouflaged in the dappled light of the water.

The squid only live for around ten months, but these intrepid explorers made the journey into space to help researchers understand how bacteria that live inside animals are affected by microgravity. Beneficial microbes inside the human body help protect us from infection, so these experiments are really important for astronaut health on long-term missions. With only three studied, no firm conclusions could be made from this first experiment, but the team are now confident that the squid and their bacteria can survive the long trip.

The squid housed in tubes of seawater

THREE

GROWING TOMATOES IN SPACE

Young people across the US and Canada are working with NASA to find ways of growing food in space. Throughout the school year, 1.2 million tomato seeds were sent out to 18,000 schools. Half of these seeds made the journey to space and back, spending five months on board the ISS under the watchful eye of astronaut Scott Kelly.

The students weren't told which were the space seeds and which stayed on Earth, so they treated both the same, planting them, then watching and recording as they germinated and grew, teaching the students about plant life cycles and how to go about conducting rigorous scientific studies.

Each school then submits its data, informing NASA how many seeds they planted, and how many actually grew. The results help scientists understand what happens to seeds when they are taken into space, and will be used to help plan missions to Mars.

During the two-year journey to the Red Planet, the crew would need to grow tomatoes that are not only nutritious, but also have leaves that can produce clean drinking water that can be captured as it evaporates.

1 Preparing the seeds 600,000 seeds were prepared and packed, ready for the journey into space.

2 To the ISS The seeds went on board the SpaceX Dragon, a privately owned cargo craft.

3 Time in space The seeds spent five weeks in microgravity.

4 Back to Earth They were sent to thousands of schools across North America.

5 The experiment Earth and space seeds were grown in the same conditions.

6 Citizen scientists Since 2001, more than 3 million students have been involved.

FOUR

HOW SPACE TRAVEL AFFECTS THE HUMAN BODY

The crew on the ISS spend over an hour every day exercising. This is not only vital for their wellbeing, but also helps scientists gather information about the effects of space on the human body.

There are three main pieces of gym equipment on board the space station – an exercise bike, a treadmill and a weights machine, each of which has been modified for the conditions on board the ISS.

The crew keep fit using specially designed equipment

A standard weight machine wouldn't work without gravity, so the ISS Advanced Resistive Exercise Device uses pistons and vacuum cylinders instead. The astronaut has to pull against the vacuum to move the machine, and specially designed flywheels help make it feel more like lifting weights on Earth.

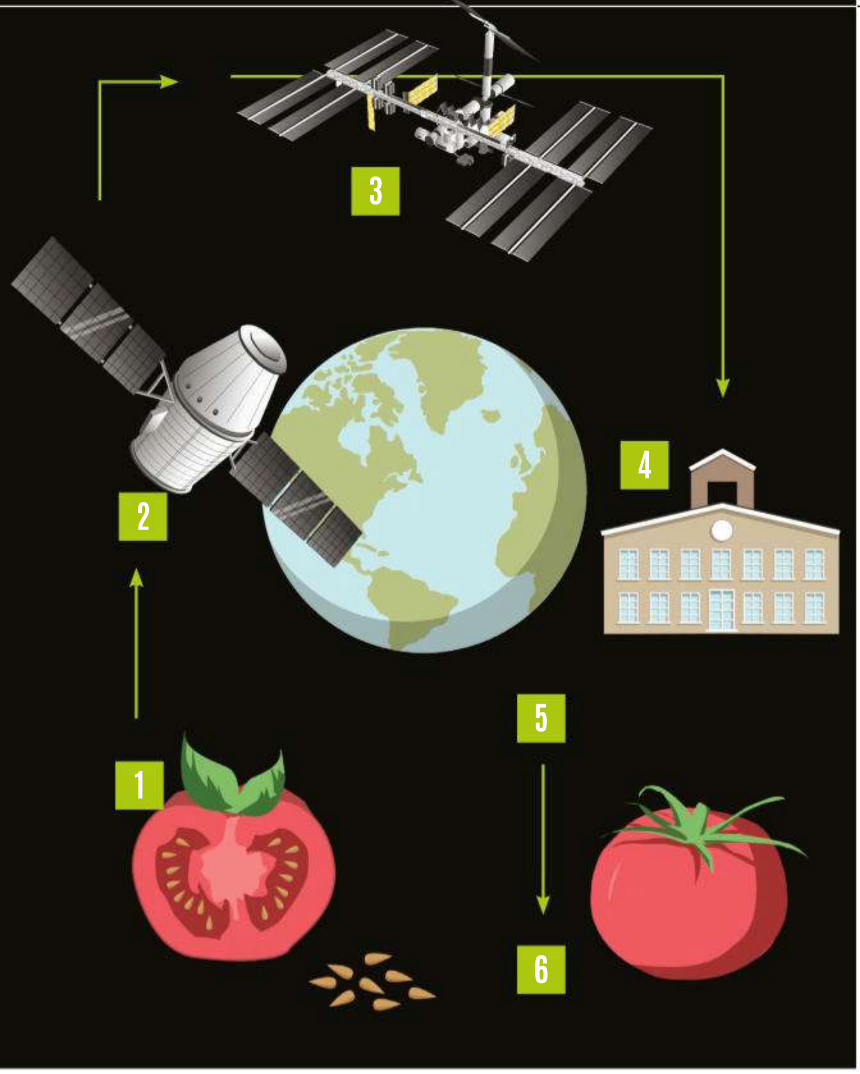
FIVE

3D PRINTING WITHOUT GRAVITY

Imagine what space travel would be like if new parts and tools could be delivered to astronauts at the touch of a button. That is the aim of Made In Space and its 3D printer on board the ISS.

In November 2014, NASA astronaut Barry "Butch" Wilmore became the first person to use a 3D printer in space. After a few test runs, a Made In Space engineer sent the plans for a wrench to the ISS for the first test of on-demand printing. Four hours and 104 layers of plastic later, the wrench was finished.

Operating a 3D printer in space is a huge technical challenge. On Earth, gravity helps the plastic to sit in neat layers as it is extruded, but on the ISS the components would float around. Made In Space has tackled this problem with some innovative but top-secret technology.



K10 borrows and advances technology from undersea exploration

Under certain conditions, flatworms can generate multiple heads

SEVEN

CONTROLLING ROVERS FROM THE ISS

In June 2013, flight engineer Chris Cassidy took control of a K10 robot at NASA's Ames Research Center in California, not from the ground, but from the ISS. He drove around a simulated moonscape for three hours, demonstrating the future technology that could allow astronauts in space to send robotic scouts to other worlds.

K10 is a four-wheel-drive robot weighing about 100 kilograms. It borrows technology from undersea exploration and can also intelligently plan its route across the terrain. K10 moves at a slow walking pace and builds a 3D picture of its environment using a combination of cameras and a laser.

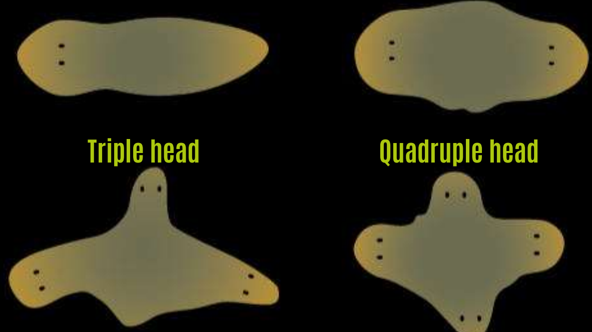
K10 is also able to deploy radio antennae, becoming a mobile communications platform. The technology is being tested for a possible NASA Orion spacecraft mission, which aims to take a crew into orbit around Earth behind the far side of the Moon. With technology like this, astronauts could use a remote-controlled robot to deploy a radio telescope onto the Moon's surface.

SIX

STEM CELLS WITH FLATWORMS

Flatworms are some of the simplest life forms on the planet, but they have an incredible ability: if you cut them in half, each piece will grow into a fully formed flatworm. This is down to stem cells positioned throughout their bodies, ready to spring into action if damage occurs by dividing and changing to form the cells needed to build new tissues and organs. Scientists are starting to understand how this process happens on Earth, but wondered if the stem cells would still function without gravity.

Flatworms travelled to the ISS and back in sealed tubes, where they were monitored to see how well they repaired themselves. The flatworms spent five weeks in space in test tubes filled with half air and half water, while another set of the creatures were sealed in the same set up in total darkness. The activation of various genes was also tracked and compared to the patterns that we see back on Earth. The spacefaring flatworms, on their return, were found to be initially paralysed and curled up before unwinding themselves, gravitating towards light, altering their metabolic rate and regrowing two heads if they were unlucky enough to be chopped up.



EIGHT

TESTING INFLATABLE HOMES

Humans will need places to live when we travel to the Moon, Mars and beyond, and where better to test them than the ISS? The Bigelow Expandable Activity Module (BEAM) was carried to the space station in 2016 on board a SpaceX Dragon. Packed up, BEAM only measures 1.7 by 2.4 metres (5.7 by 7.8 feet), but when filled with pressurised air it inflates to form a space 3.7 by 3.3 metres (12 by 10.5 feet), about the size of a small bedroom.

It's made up of many layers, including an air cushion and a shield that will protect the structure from damage by dust and debris. In the case of a collision with a larger object, the inflatable room is designed to leak air slowly, allowing the astronauts on the space station plenty of time to react.

The module was docked with the ISS' Tranquility node, but wasn't ready for use straight away. A number of tests are being carried out on BEAM, which include temperature, pressure and radiation readings being recorded around the clock. Astronauts enter every three months to take measurements and perform an inspection of its condition. All being well, inflatable rooms might become an integral part of our space habitats.

BEAM was carried to the space station in 2016 on board a SpaceX Dragon

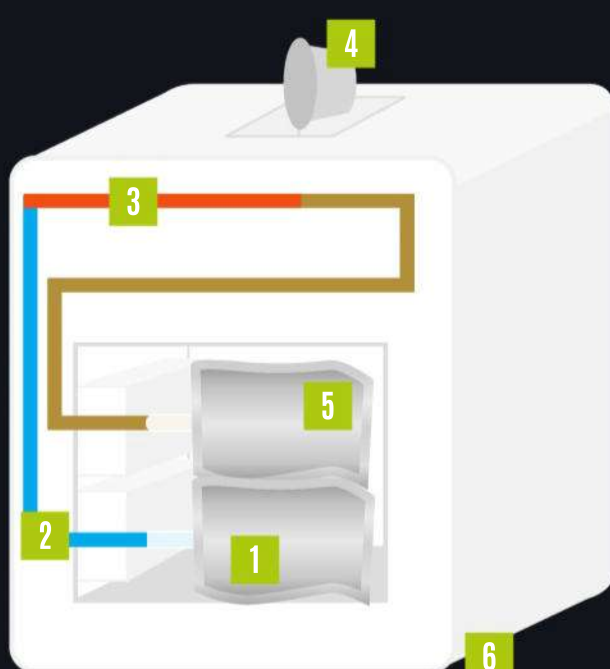
There's no need to miss a caffeine fix, even in space

NINE

MAKING COFFEE IN EARTH ORBIT

Making hot drinks in space is a complex business, but not content with the idea of a life without coffee, the Italian Space Agency teamed up with space food engineering company Argotec and coffee giant Lavazza to design a machine that could be used in microgravity. Water at high temperatures and pressures is difficult to manage in space, so the project was a serious engineering challenge. Plastics had to be replaced with steel tubing capable of withstanding pressures of up to 400 bar – 400 times the air pressure at sea level – and the finished product weighs a hefty 25 kilograms.

The ISSpresso machine works in a similar way to coffee machines on Earth, and even uses the same Lavazza coffee capsules. It can also make tea and broth. An astronaut in need of a hot beverage just has to follow these simple instructions: plug the machine into a utility outlet panel and install a water pouch. Then install a NASA standard drink bag and a capsule containing the desired drink. Three minutes later, the drink is ready. Italian astronaut Samantha Cristoforetti was the first to enjoy a coffee in space.



1 Water pouch
The astronaut first fills a pouch with water, then fastens it to the coffee machine.

2 Water in
The water is pressurised, passing through a series of steel tubes into the heater.

3 Heating
Once the water has been pressurised, it's heated to the right temperature.

4 Coffee capsule
Hot water passes through a capsule, and fresh coffee is pushed into the pouch.

5 Pressure difference
A differential means that when the straw goes in, the fresh coffee smell rushes out.

6 Coffee time
The whole process takes three minutes, barely longer than you have to wait for a coffee back on Earth.

TEN

HUNTING FOR DARK MATTER

Something about the universe doesn't quite add up. Everything that we can see – from stars and planets to galaxies and black holes – only represents around five per cent of what is known to be the total mass and energy. Where – and what – is the other 95 per cent?

A total of 56 institutes from 16 countries around the world have come together to find the answer. The Alpha Magnetic Spectrometer (AMS-02) weighs 8,500 kilograms and was delivered to the ISS on the penultimate voyage of the Space Shuttle Endeavour. Since 2011, AMS-02 has been monitoring for signs of antimatter, dark matter and dark energy – the missing pieces of the universe.

Assembled at CERN, the home of particle physics, AMS-02 is a particle detector. At its core is a huge magnet that measures the charge of any particle coming in, and an arsenal of instruments identify other properties, including a 'stopwatch' that times the particles as they pass through.

AMS-02 is searching for cosmic rays, extremely high-energy radiation, some of which may be charged particles released when dark matter collides. So far it has recorded over 100 billion events, and will continue trying to understand the missing portion of the universe.

> "Since 2011, AMS-02 has been monitoring for signs of antimatter, dark matter and dark energy"

1 Transition radiation detector
This detector can tell the difference between particles by the X-rays they release.

2 Time-of-flight scintillator
Measures how long each particle takes to pass through the detector.

3 Silicone tracker
Measures the paths of particles as they are bent by the magnet.

4 Permanent magnet
Bends the path of charged particles as they pass.

5 Ring-imaging Cherenkov counter
Identifies the type of charged particle by measuring the radiation it emits.

@ Ed Crooks; NASA; ESA

FOCUS ON

HUBBLE SPOTS STAR THAT SURVIVED A VIOLENT EXPLOSION

NASA's most iconic space telescope has uncovered an object that survived the violent death of its companion

Reported by Samantha Mathewson

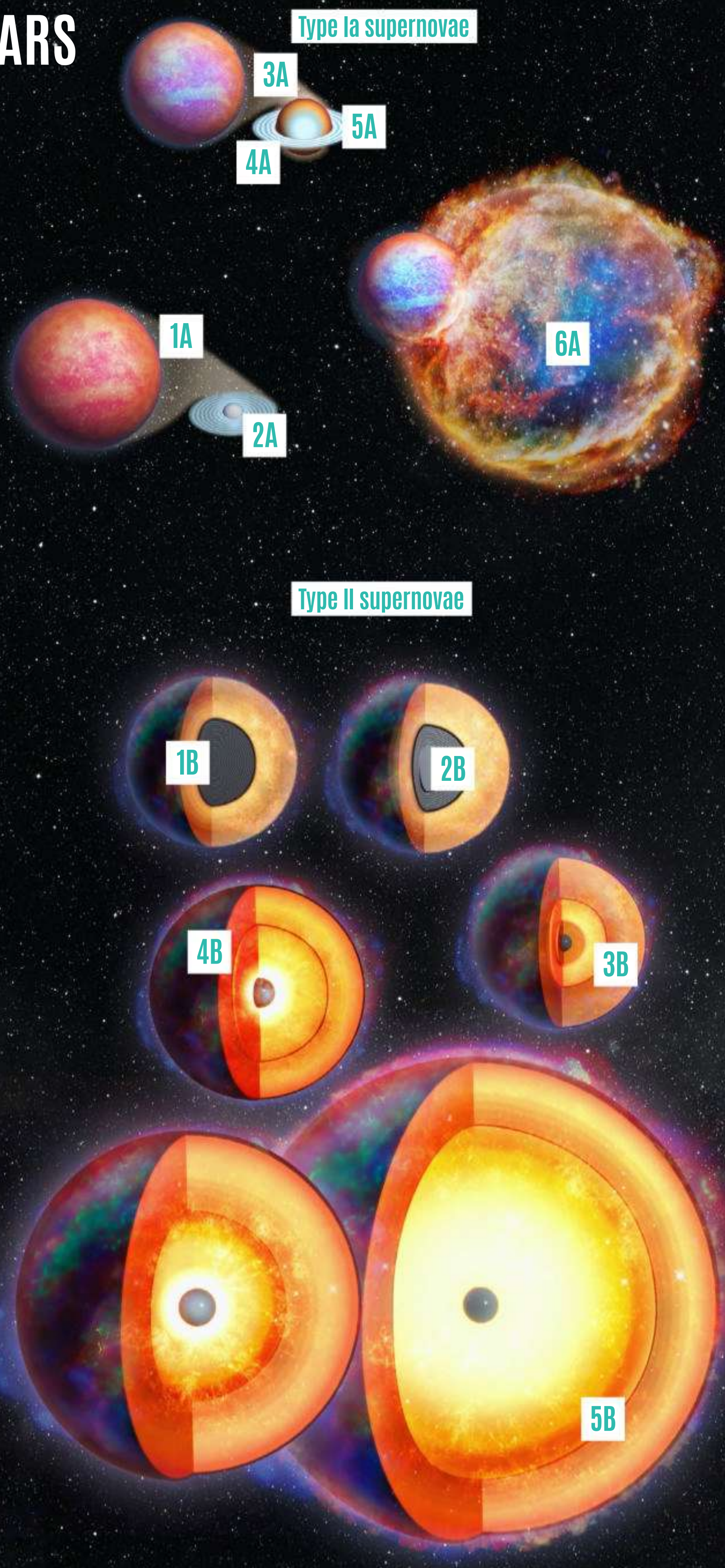
When a massive star reaches the end of its life, it explodes in a brilliant burst of light known as a supernova. This bright explosion can briefly outshine entire galaxies, which is how the star's surviving partner remained hidden from view. Using Hubble's Wide Field Camera 3, researchers were able to study the supernova SN 2013ge in ultraviolet light. The scientists found that while the light from the bright stellar explosion has been fading since 2016, another nearby source of ultraviolet light has maintained its brightness over time, suggesting SN 2013ge has a surviving binary companion.

"This was the moment we had been waiting for, finally seeing the evidence for a binary system progenitor of a fully stripped supernova," Ori Fox, lead investigator on the Hubble research program, said. "The goal is to move this area of study from theory to working with data and seeing what these systems really look like." Using the Hubble data, astronomers were able to identify the signature of various elements in the supernova explosion. Strangely, no hydrogen was detected in the region of SN 2013ge, leaving scientists to guess at how the gas might have been stripped away before the explosion occurred.

The observations shed new light on the nature of massive stars in binary systems. Observations of SN 2013ge also help explain how some stars are stripped of their hydrogen presupernova, which in this case is the result of an unseen stellar companion siphoning gas from its partner before it explodes. "Many different lines of evidence have told us that stripped supernovae are likely formed in binaries, but we had yet to actually see the companion," Maria Drout, an astronomer from the University of Toronto, said. "So much of studying cosmic explosions is like forensic science – searching for clues and seeing what theories match," Drout added. "Thanks to Hubble, we are able to see this directly."

Astronomers can now use SN 2013ge's surviving companion to better understand the characteristics of the star that exploded. And the researchers will be able to track the surviving star's evolution. Depending on the distance between the original companion stars, the surviving partner will either be flung out of the system – which could help explain why solitary supernovae are observed across the universe – or continue orbiting its companion before merging to create gravitational waves. However, such an event would not occur for a billion years, the researchers said. "Understanding the life cycle of massive stars is particularly important to us because all heavy elements are forged in their cores and through their supernovae," Alex Filippenko, coauthor of the study and an astronomer at the University of California, Berkeley, said. "Those elements make up much of the observable universe, including life as we know it."

HOW DO STARS EXPLODE?



Type Ia supernovae

1A Finding the right stars
These occur when a white dwarf is found in a binary pair with another star.

2A Matter transfer
Occasionally the two stars will orbit close enough that matter will transfer from the companion onto the white dwarf.

3A Squeezing down
This accretion of matter adds extra mass. The additional gravitational forces compress the already highly pressurised core of the white dwarf.

4A A star reborn
The dying star comes to life again and undergoes fusion in its centre.

5A Limited gains
White dwarfs can only get so massive through accretion, about 1.4 times the mass of our Sun.

6A Outward pressure
The star can no longer expand. Expansive forces build, creating a violent supernova.

Type II supernovae

1B Out of gas
Supergiants eventually run out of fuel, the burning of which prevents them collapsing.

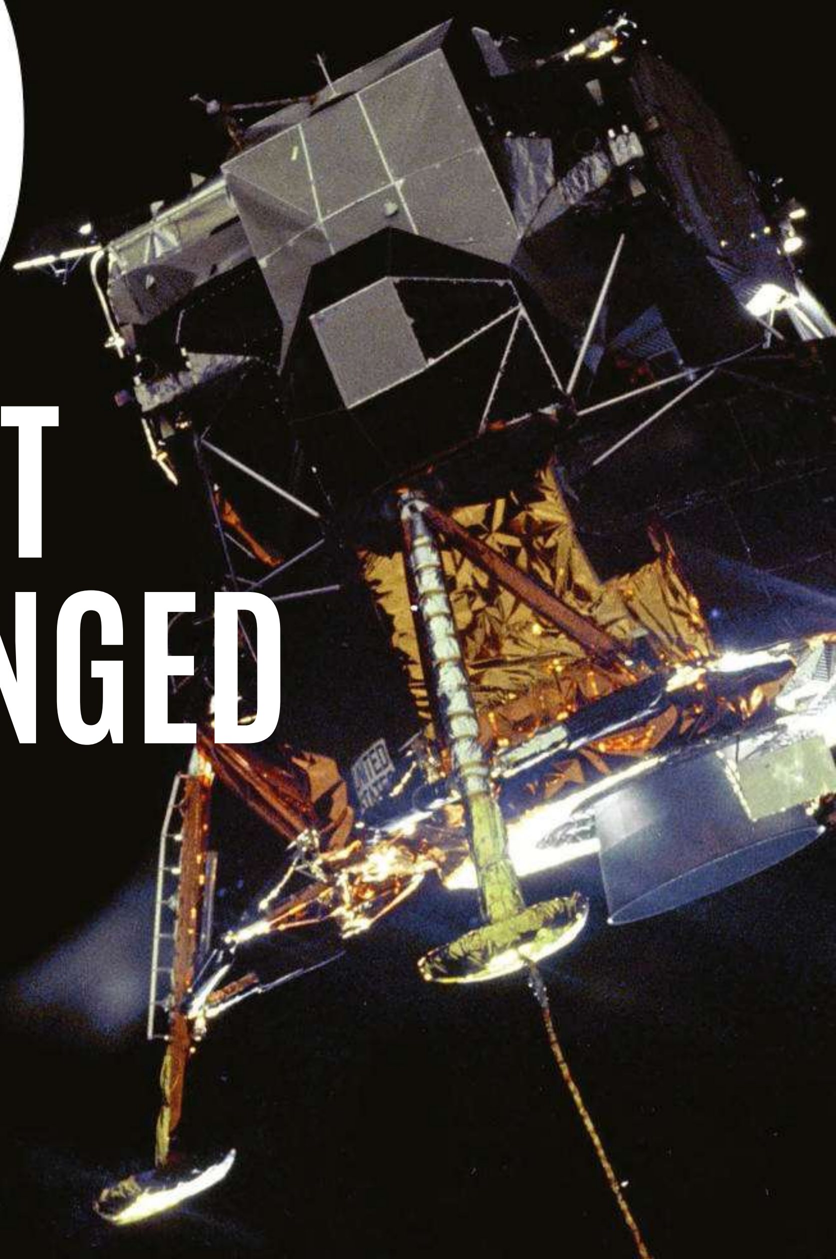
2B Elemental onion
Heavier elements build up at the star's centre, which becomes layered, with lighter elements towards the outside.

3B Resistance is futile
This act of resistance holds until the star's innermost core is composed of iron, which won't fuse. Gravity wins and the star's outer layers collapse inwards.

4B Burning fuels
For stars this size, their mass and compressional forces at the core allow them to fuse heavier elements in order to maintain outward pressure.

5B Shock wave rebound
This inward implosion bounces back off the core as a rebounding shock wave that blows the whole atmospheric envelope off the star in a supernova.

10 SPACECRAFT THAT CHANGED THE WORLD



The past, present and future of the world's greatest spacecraft, from the early pioneers to the modern marvels

Written by Nigel Watson

1 APOLLO 11 LUNAR MODULE

The first manned spacecraft to land on the Moon

To perform the first Moon landing, the Apollo 11 mission used two very different spacecraft. The first was the pressurised, conical-shaped Command Module that served as the main living quarters. It was attached to an unpressurised Service Module containing the main rocket engine and propellant.

At launch, the Apollo 11's Command and Service Module (CSM) was mounted above the Lunar Module (LM) on top of the Saturn V rocket. When they moved out of Earth orbit, the CSM separated itself and turned around to attach to the docking port on the LM.

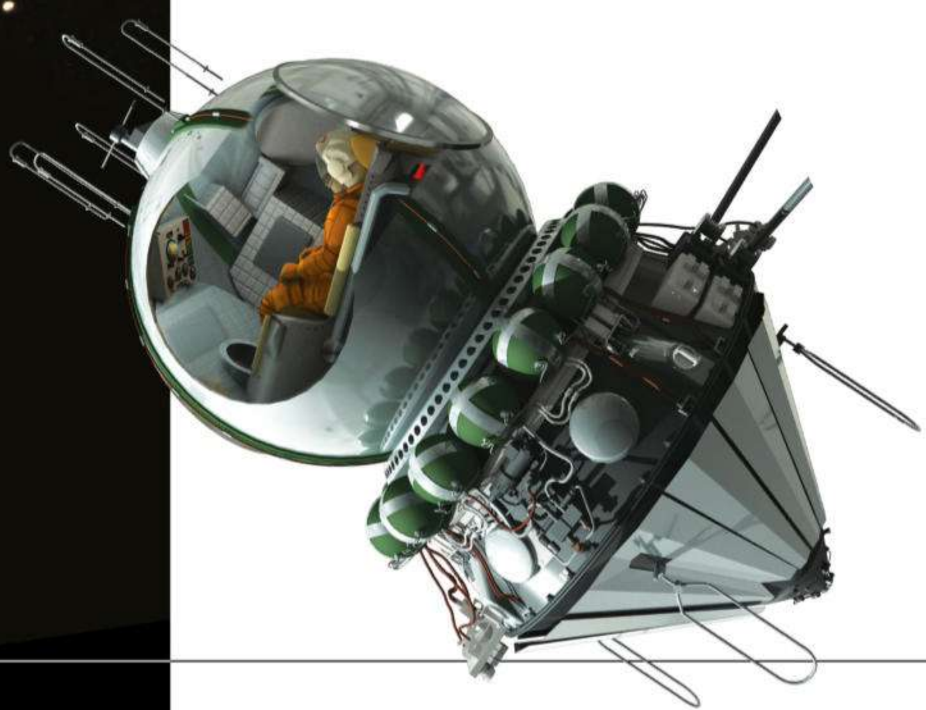
On 20 July 1969 at 20:17 (UTC), Neil Armstrong and Edwin 'Buzz' Aldrin touched down on the Sea of Tranquillity and deployed exploration equipment from a bay on the side of the descent module. On leaving the Moon, the ascent stage's own rocket motor blasted off the descent stage, which remained behind on the Moon. After docking with the CSM, the ascent stage was jettisoned and left to crash back into the Moon. Prior to re-entry the Service Module was jettisoned, and after re-entry the Command Module parachuted down to a splashdown in the sea.

2 SATURN V
A true powerhouse

The mighty three-stage Saturn V rocket towered to a height of 110.6 metres (363 feet) and weighed 3 million kilograms fully fuelled. It was constructed under the direction of Wernher von Braun, the German rocket pioneer, at Marshall Space Flight Center in Huntsville, Alabama. A workforce of 5,000 people took four months to fit the Saturn V's rocket stages together in the Vehicle Assembly Building at Kennedy Space Center in Florida.

Altogether, 15 Saturn V rockets were built. The next closest in size to it was the Soviet Union's N1 Moon rocket that measured 105 metres (344 feet) tall, but it exploded on all four attempts to launch it. In comparison, the Space Shuttle was only 56 metres (184 feet) tall. The Ares I, at 94 metres (308 feet) tall, came close, but it was cancelled due to NASA budget cuts. The soon-to-launch Space Launch System rivals its size at 111.3 metres (365 feet).

"Vostok 1 was almost entirely autonomous to prevent any human error"



3 VOSTOK 1
The original manned spacecraft

Vostok 1 was the spacecraft that took the first-ever human into space – Yuri Gagarin on 12 April 1961. Although troubled by performance issues, Vostok 1 was a technical marvel. Never before had a vehicle been able to take a human to orbit and return them intact, and therefore Vostok 1 was almost entirely autonomous to prevent any human error. Gagarin could only take control in an emergency, unlike Alan Shepard a few weeks later in the Freedom 7 spacecraft, who had almost full control of his flight.

Although Gagarin spent just an hour and 46 minutes in orbit he – along with Vostok 1 – will forever be remembered for kick-starting the age of human space exploration.

4

SPUTNIK 1

This pioneering human-made object was the first to go into Earth orbit

On 4 October 1957, the Soviet Union successfully sent the first-ever artificial object into Earth orbit, using an R-7 rocket to get it there. The small, spherical satellite with four pronged legs was named Sputnik 1.

It was a major milestone, not only for the Soviets but also for humanity as a whole, signifying that Earth orbit was both possible and feasible. Sputnik 1 led directly to the Space Race between America and the Soviets. However, it also gleaned some scientific data, such as measuring the electron density in the ionosphere.

It entered an elliptical orbit, reaching over 900 kilometres (560 miles) from the surface of Earth. It transmitted radio signals for 22 days that were monitored around the world and eventually fell back into the atmosphere and burned up on 4 January 1958.

5

VOYAGER 1 & 2

Reaching the edge of the Solar System and beyond

The two unmanned Voyager spacecraft have been on a long journey to escape our Solar System and enter the realms of interstellar space. After achieving the primary mission to explore Jupiter and Saturn, they progressed to explore and image the outer planets and are now studying the outer limits of the Sun's solar wind and magnetic field as part of the Voyager Interstellar Mission (VIM).

They have now both passed through the heliosheath, where the compressed solar wind turbulently interacts with the interstellar medium, and crossed the heliopause, which is considered to be the edge of the Solar System. Both are still sending back data to Earth – the first craft able to give us clues about the interstellar medium that fills space beyond our Sun's influence. Voyager 1 entered interstellar space first on 25 August 2012, with its twin spacecraft following on 5 November 2018 at a distance 122 times the Sun's distance from Earth.

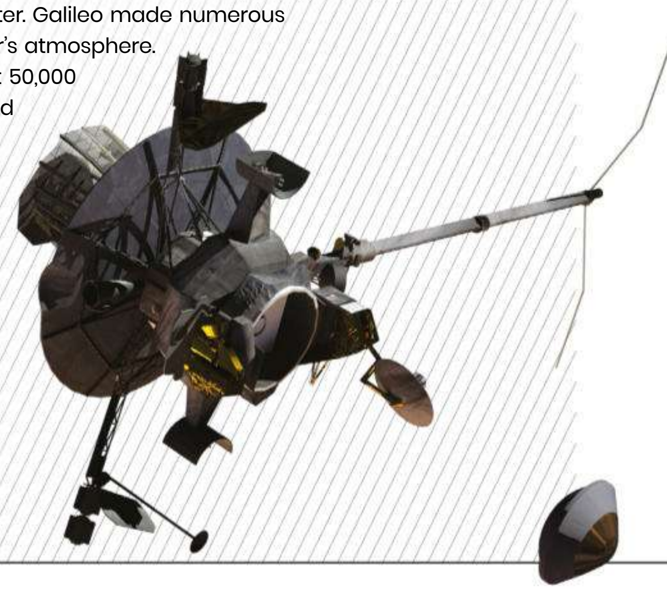
6

GALILEO

The first craft to enter Jupiter's atmosphere

Galileo was taken into space by Space Shuttle Atlantis on 18 October 1989. The unmanned craft consisted of a main orbiting vehicle and a Jupiter atmosphere probe. During its journey, it discovered a huge impact basin on the Moon's far side. It passed within 1,600 kilometres (990 miles) of the Gaspra asteroid, and when passing the Ida asteroid at a distance of 2,400 kilometres (1,500 miles) Galileo's instruments discovered a small moon, Dactyl, orbiting it.

On 8 December 1995, Galileo fired its main engine to become the first human-made object to orbit Jupiter. Galileo made numerous discoveries about the nature of Jupiter's atmosphere. These included finding a radiation belt 50,000 kilometres (31,000 miles) above its cloud layer, strong winds blowing at 600 kilometres (400 miles) per hour and ten per cent less lightning activity than on Earth, though it can be up to a thousand times more powerful. After making 34 orbits of Jupiter, Galileo was nearly empty of fuel, so it was decided to crash the craft into Jupiter. After travelling a total of 4.6 billion kilometres (2.8 billion miles), Galileo disintegrated in Jupiter's dense atmosphere on 21 September 2003.



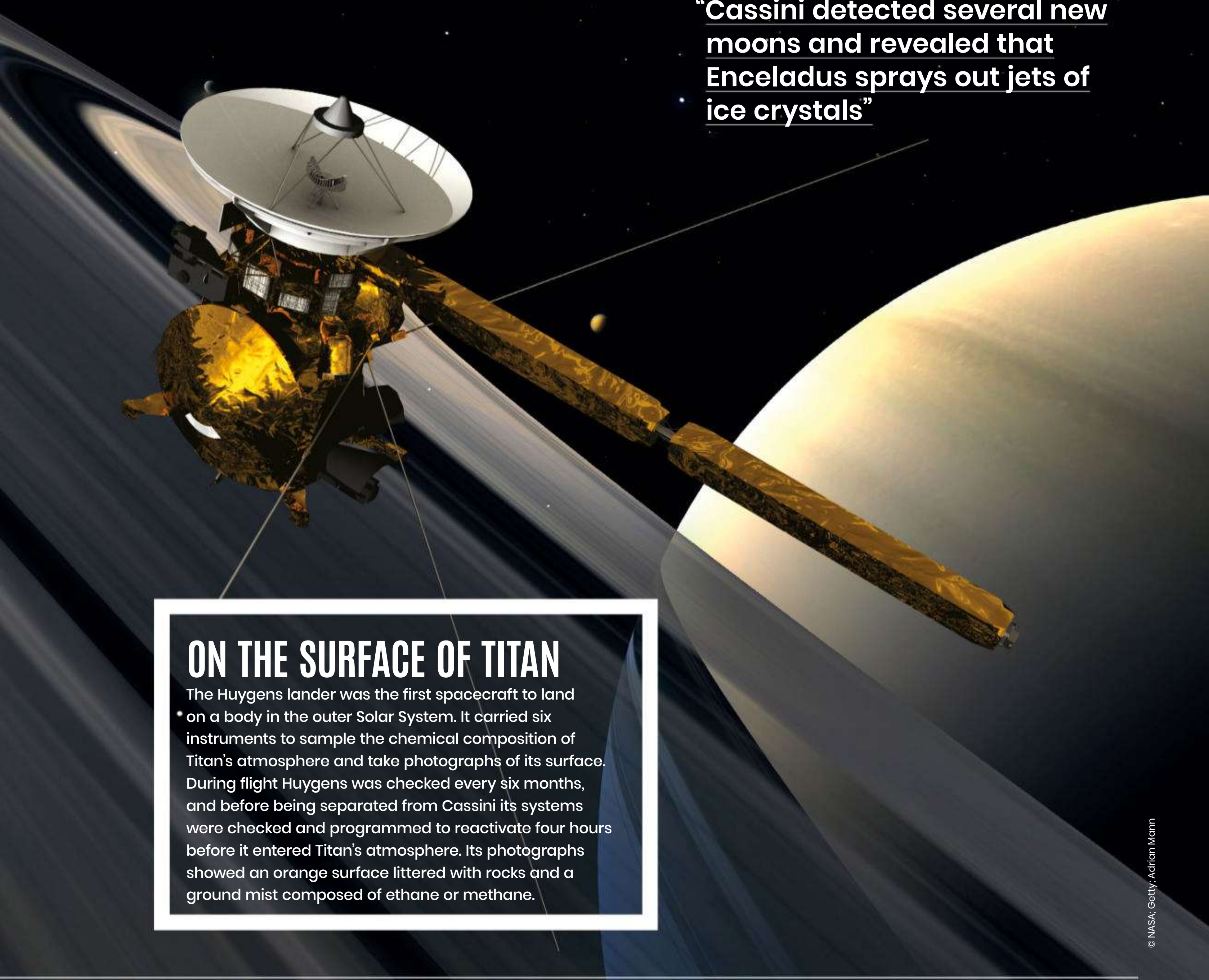
7 CASSINI-HUYGENS

A complex interplanetary probe

At 6.7 metres (22 feet) tall and four metres (13 feet) wide and with a weight of 5,712 kilograms, Cassini is the largest and most complex unmanned interplanetary spacecraft ever launched. Its main objective was to use 12 onboard scientific instruments to conduct a four-year long study of Saturn's atmosphere, surface details, the behaviour of its rings, magnetic environment and the composition of its moons, as well as to carry the Huygens lander to Saturn's moon Titan.

It began orbiting Saturn on 1 July 2004 and completed its prime objectives on 30 June 2008. Early in 2012, it studied the moons of Jarnsaxa and Mundilfari and passed Enceladus. Cassini detected several new moons and revealed that Enceladus sprays out jets of ice crystals that feed into the rings of Saturn. On Saturn, lightning storms and hurricanes were discovered, and on Titan they have found mountains, clouds, snow and liquid methane rivers and lakes under its smoggy atmosphere, much like the conditions on Earth before life evolved here. To end the mission, NASA crashed Cassini into Saturn in 2017.

"Cassini detected several new moons and revealed that Enceladus sprays out jets of ice crystals"



ON THE SURFACE OF TITAN

The Huygens lander was the first spacecraft to land on a body in the outer Solar System. It carried six instruments to sample the chemical composition of Titan's atmosphere and take photographs of its surface. During flight Huygens was checked every six months, and before being separated from Cassini its systems were checked and programmed to reactivate four hours before it entered Titan's atmosphere. Its photographs showed an orange surface littered with rocks and a ground mist composed of ethane or methane.

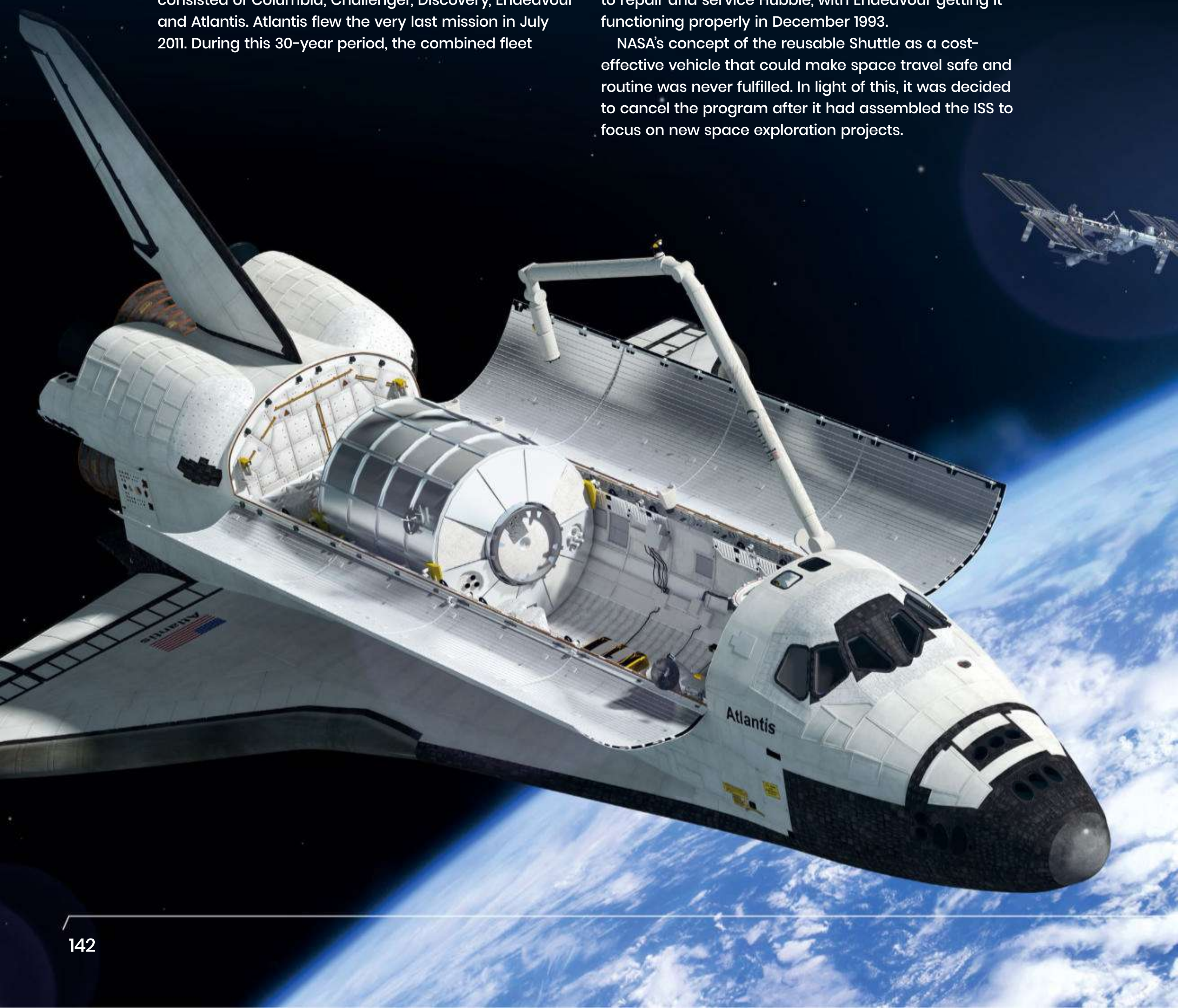
8 SPACE SHUTTLE
The first reusable manned spacecraft

Columbia was the very first Space Shuttle to blast off from the Kennedy Space Center on 12 April 1981. It was mounted on a huge 47-metre (154-foot) long and eight-metre (27-foot) diameter external tank and two solid booster rockets to take it into orbit. The boosters were jettisoned into the Atlantic Ocean where they were recovered and reused, and nine minutes after launch the external tank fell away into the atmosphere and burnt up over the Pacific Ocean. After its mission, the Shuttle 'orbiter' landed on a runway like a conventional aircraft. It could then be refurbished to be launched once more into space.

The flight of Columbia proved that the 2.5 million parts of the Space Transportation System (STS) – as it was officially called – were fully functional. The Shuttle fleet consisted of Columbia, Challenger, Discovery, Endeavour and Atlantis. Atlantis flew the very last mission in July 2011. During this 30-year period, the combined fleet conducted 133 successful missions, made over 21,000 Earth orbits, travelled almost 873 million kilometres (543 million miles) and carried more than 850 astronauts.

Two major disasters struck the Shuttle program. Challenger broke up and exploded during liftoff on 28 January 1986, while Columbia disintegrated during re-entry on 1 February 2003. Nonetheless, the Shuttle craft made many notable achievements, including 37 missions to the International Space Station (ISS). On 25 April 1990, Space Shuttle Discovery deployed the Hubble Space Telescope, the world's first space-based optical telescope. In May 1992, Endeavour, built to replace Challenger, sent three astronauts to recover, repair and re-launch the INTELSAT VI communications satellite. From 1993 to 2009, the Shuttle program made five trips to repair and service Hubble, with Endeavour getting it functioning properly in December 1993.

NASA's concept of the reusable Shuttle as a cost-effective vehicle that could make space travel safe and routine was never fulfilled. In light of this, it was decided to cancel the program after it had assembled the ISS to focus on new space exploration projects.



9 ORION
A new dawn of space exploration

Currently getting ready to ferry astronauts back to the Moon, the Orion spacecraft is world-changing in terms of its advanced design and scale of ambition. Unlike other craft of its kind, Orion has been designed for long-term space missions lasting over six months, which could see the vehicle being used for manned trips to Mars during its service lifetime.

It will use a revolutionary abort system that fires the capsule away from danger during the launch and liftoff stages. At its base, Orion has an adaptor unit so that it can be fitted to different launch vehicles.

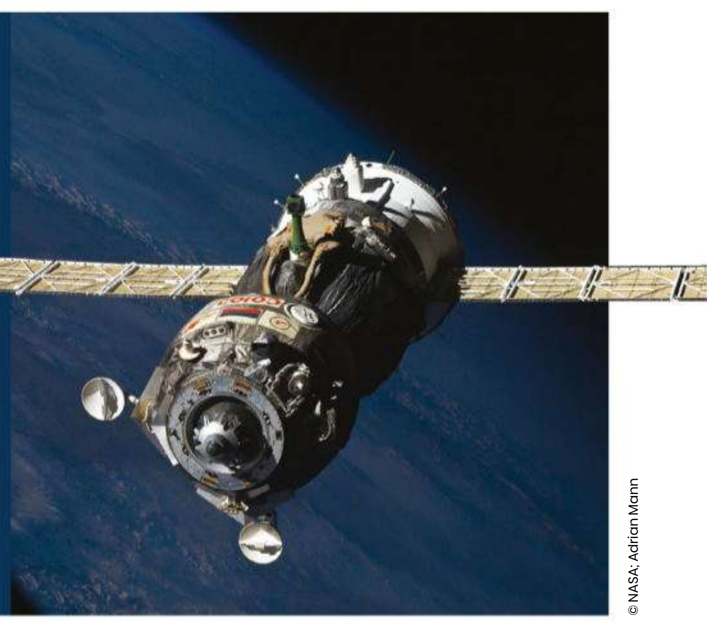
The craft has a unique life-support system and thermal protection, along with advanced propulsion and navigation systems. When necessary, Orion can send backup crews and cargos to the ISS and can also be used to take astronauts to the Moon, near-Earth asteroids, the moons of Mars and Mars itself.

“Orion has been designed for long-term space missions lasting over six months”

10 SOYUZ
The longest serving manned spacecraft

The Soyuz was designed as an essential part of the mission to land Soviet astronauts on the Moon. A modified two-man version was planned to be the equivalent of the Apollo Command Module, which would release a manned lander to the Moon. After the cancellation of the Moon program, the Soyuz became a manned ferry to the Salyut space station.

The basic craft carries three crew in a spherical orbital module who are returned to Earth in a re-entry module that is positioned behind it. It can automatically dock to a spacecraft, though a manual override can be used when needed. The Soyuz has remained successful due to its modular design and ability to be modernised and modified to adapt to changing mission requirements.



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